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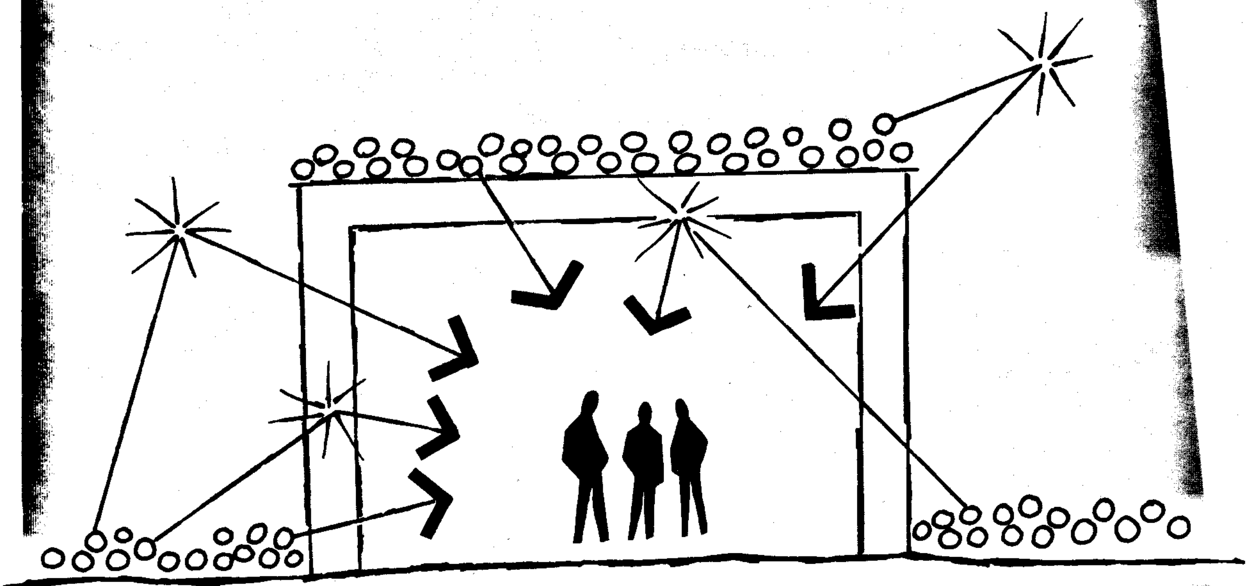
SHELTER DESIGN AND ANALYSIS



FALLOUT RADIATION SHIELDING

DEFENSE
CIVIL PREPAREDNESS
AGENCY

WASHINGTON, D.C.

PREFACE

This manual revises and supersedes TR-20 (volume 1) dated June 1968, and changes 1, 21 and 3 thereto, as well as appendix C, which may be used.

In this revision, some of the highly theoretical materials have been reduced to simple explanations in order to aid the analyst in developing a sense of qualitative interpretation unencumbered by rigorous mathematical expressions. The radiation shielding analysis methodology is developed in logical order, with many illustrative problems designed to emphasize particular stages of development and methods for solution. Where appropriate, study questions and problems have been included. These have been designed to give the analyst a means for testing his knowledge.

Although most students of shielding analysis have sufficient background in nuclear physics through formal courses of instruction, a brief, basic review of the subject matter is provided in appendix A of this manual.

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LIST OF SYMBOLS

A — The area of a structure

A_P — The ratio of the area of apertures in an exterior wall to the tota wall area

A_z — Azimuthal sector, the ratio of a plane angle at the detector subtending a wall segment to 360 degrees

B — Any barrier reduction factor

B_c — Barrier reduction factor for ceilings

B_e — Barrier reduction factor for exterior walls

B_f — Barrier reduction factor for floors

B_I — Barrier reduction factor for ground contribution through interior partitions

B_I' — Barrier reduction factor for overhead contribution through interior partitions

B_s — Barrier reduction factor for scatter radiation through exterior walls subject to limited field

C — Any contribution of radiation to a detector

C_a — The contribution through an aperture strip that is completely zero in mass thickness

C_a' — The contribution through an aperture strip that is completely solid

C_g — The total ground contribution to a detector

C_o — The overhead contributicn to a detector

d — The dose rate received at a point at any time, t, after an explosion

d_1 — The dose rate received at a point one hour after an explosion

D — The total accumulated radiation dose over a given time interval

e	—	Eccentricity ratio, ratio of width to length of a structure
E	-	Shape factor applied to scatter geometry
ERD	—	Equivalent Residual (radiation) Dose
G	-	Any geometry reduction factor
G_a	-	Geometry factor for skyshine radiation
G_d	—	Geometry factor for direct radiation
G_g	—	Total geometry reduction factor for ground contribution
G_s	-	Geometry factor for scatter radiation
H	-	Height of detector above the contaminated plane
H_f	—	Fictitious height of air replacing an equivalent mass thickness
KT	—	Kiloton, explosive energy equivalent of one thousand tons of TNT
L	—	Length of a rectangular structure
L_c	—	Length of a limited field of contamination
MeV	—	Million electron volts
MT	—	Megaton, explosive energy equivalent of one million tons of TNT
P_a	—	Ratio of total width of windows in an aperture strip to total perimeter of the aperture strip
P_f	—	Protection factor
P_r	-	Perimeter ratio, ratio of the length of any wall segment to the tota perimeter of a structure
R	—	Roentgen, a unit of measurement for radiation
R_f	—	Reduction factor, sum of all contributions
S_w	—	Scatter fraction, fraction of wall emergent radiation that has been scattered in the wall

t — Any time after an explosion

t_i — Time, after explosion, of initial exposure to radiation

t_f — Time, after explosion, of final exposure to radiation

W — Width of a rectangular structure

W_c — Width of a limited field of contamination

X — Any mass thickness in pounds per square foot of surface area of barrier

X_c — Mass thickness of a ceiling barrier

X_e — Mass thickness of an exterior wall

X_f — Mass thickness of a floor barrier

X_i — Mass thickness of an interior partition barrier

X_o — Total overhead mass thickness

X_r — Mass thickness of roof barrier

X_w — Mass thickness of any wall in general

Z — Distance from the detector to an overhead plane of contamination

ω — A solid angle fraction at the apex of a pyramid or cone

ω_s — Solid angle fraction subtended by a limited field of contamination

CHAPTER I

GENERAL EFFECTS OF NUCLEAR WEAPONS

1-1 Introduction

The following description of the general effects of nuclear weapons is intended to furnish the analyst with enough background information to enable him to recognize the destructive power of nuclear detonations, and to understand the general nature of the fallout problem - why it may exist, how it is developed, its extent, its probable effects on human life, and the need for fallout protection. Further information is found in The Effects of Nuclear Weapons, published by the United States Atomic Energy Commission, April **1962,** and obtainable from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. Appendix A of this manual provides a brief review of nuclear physics for those analysts who may find it necessary for a better understanding of the material in this and following chapters.

1-2 Nuclear and Conventional Explosions Compared

1-2.1 Derivation of Energy

All substances are made up from one or more of over 100 different kinds of materials known as elements. The smallest part of any element that can exist, and not be divisible by chemical means is called an atom.

According to present-day theory an atom contains a relatively dense central core, called the nucleus and a much less dense outer domain consisting of electrons in motion around the nucleus. Nuclei are composed of a definite number of fundamental particles, --- principally protons and neutrons. The proton carries a positive charge of electricity. The neutron, as its name implies, is electrically uncharged. The masses of protons and neutrons are about the Same. The electrons are light, negatively charged particles. The total charge on electrons in a normal atom, balances the total positive charge of the nucleus.

An explosion is produced when a large amount of energy is suddenly released within a limited space. This is true both for conventional and nuclear explosions; however, the energy released in each type of explosion

is produced in different ways. In conventional explosions, the energy is released as the result of chemical reactions, In a nuclear explosion, energy is produced as the result of nuclear reactions.

Electromagnetic forces (a few eV) bind atoms together to form chemical compounds. In chemical reactions, these chemical bonds are broken and new ones are formed as original compounds are converted to others. Nuclear forces (a few MeV) bind the constituent parts of a nucleus together. Nuclear reactions involve the breaking and forming of nuclear bonds as original atoms are converted to others. Nuclear forces are so much stronger than electromagnetic forces that even like-charged particles can be bound together. For example, eight positively charged protons are contained in the small nucleus of the oxygen atom. Because of the fact that nuclear forces are several orders of magnitude greater than electromagnetic forces, it follows that the energy released from an explosion produced by nuclear reactions is several orders of magnitude greater than that from a conventional explosion resulting from chemical reactions.

1-2.2 Energy Distribution

In conventional explosions, nearly all of the energy released appears immediately. Almost all is converted via heat into blast and shock. In nuclear explosions, only about 85% of the energy released appears at once. Of this 85%, about 50% is converted into blast and shock and 35% into thermal radiation in the form of heat and light. The remaining 15% of energy is released as various nuclear radiations, 5% as "initial radiation" within the first minute after the explosion and 10% as "residual radiation" after the first minute and over a period of time.

1-2.3 Temperature and Pressure Comparisons

In conventional explosions, temperatures reach a maximum of about 9000°F. Maximum temperatures in nuclear explosions reach several million degrees. The tremendous heat generated in a nuclear explosion converts the weapon constituents into a gaseous form.

The pressures produced in conventional explosions reach a maximum of several hundred atmospheres. Those produced in the detonation of a nuclear weapon reach maximums of several hundred thousand atmospheres.

1-3.1 General

Many nuclear reactions are known but not all are accompanied by explosive release of energy. The release of energy in explosive quantities requires that a very large number of nuclear reactions occur essentially instantaneously.

Two nuclear processes satisfy the above condition. These are known as the fission process and the fusion process. The fission process takes place with some of the nuclei, such as those of certain isotopes of uranium and plutonium. The fusion process takes place with some of the nuclei such as those of certain hydrogen isotopes.

1-3.2 The Fission Process

Fission is the splitting of a heavy nucleus into two approximately equal parts (which are nuclei of lighter elements) accompanied by the release of a relatively large amount of energy and generally one or more neutrons.

Fission can be caused by the absorption of a neutron by the nucleus of a fissionable atom. The neutrons released in fission are able to produce fission of more nuclei. This results in the release of more energy and more free neutrons. The process results in a continuous chain of nuclear fissions with the number of nuclei involved, and the amount of energy released, increasing at a tremendous rate.

Actually, not all the neutrons liberated in the process are available for creating more fissions. Some escape and others are lost in nonfission reactions. For simplicity, however, if one free neutron is captured by the nucleus of a uranium atom, and two neutrons are liberated, then each of these neutrons causes fission, the result is the release of four neutrons. The number of neutrons released doubles in each generation. In less than 90 generations, enough neutrons would have been produced to fission every nucleus in about 110 pounds of uranium resulting in the release of the same amount of energy as would result from the explosion of 1 million tons of TNT (1 megaton). (A 1 kiloton explosion is equivalent, in energy released, to 1000 tons of TNT.)

The time required for the actual fission process is very short. The interval between successive generations is a function of the time necessary for the released neutron to be captured by a fissionable nucleus. This time

depends, among other things, on the energy or speed of the neutrons. If they are of the high energy or fast type, the interval is about one hundredth of a millionth part of a second. In this event, the ninetieth generation would be attained in about one millionth of a second. The release of the energy equivalent to a million tons of TNT in a millionth of a second would create a tremendous explosion.

1-3.3 The Fusion Process

Fusion is the formation of a heavier nucleus from two lighter ones with the attendant release of energy. Hydrogen isotopes; i.e. protium, deuterium, and tritium, are commonly used for fusion reactions.

In order for fusion reactions to occur, the nuclei of the interacting isotopes must have high energies. These energies can be supplied by a charged-particle accelerator,or by temperatures in the order of several million degrees. Fusion reactions obtained under the latter circumstance are referred to as thermonuclear reactions.

Since a fission reaction produces temperatures of the required magnitude, a fission device can be combined with quantities of deuterium and/or tritium; and, under the proper conditions, produce thermonuclear fusion reactions, accompanied by energy evolution. The devices producing such explosions have been variously termed hydrogen bombs or thermonuclear weapons.

A comparison of the energy released in an average fusion reaction to that from a fission reaction reveals that, on a weight for weight basis, the fusion reaction produces about three times as much energy as the fission reaction.

Three of the four thermonuclear fusion reactions that are of interest in thermonuclear weapons produce free neutrons. These neutrons can cause fission of uranium to increase to the overall energy yield of the device.

1-4 Types of Nuclear Explosions

1-4.1 General

The immediate pheonomena associated with the detonation of a nuclear weapon vary with respect to the point of detonation in relation to the surface of the earth. Similar variations exist with respect to following phenomena such as the effects of shock, blast and thermal and nuclear radiation.

For convenience of description, nuclear bursts are sometimes categorized into five distinguishing types, although many intermediate situations can arise in the actual employment of nuclear weapons. The five types, described in a general way in this section, are high-altitude bursts, air bursts, surface bursts, underwater bursts, and underground bursts.

1-4.2 High-altitude Bursts

A burst is defined as high-altitude if the density of the air is so low that the interaction of the weapon energy with its surroundings is markedly different from that experienced when a weapon is detonated at lower altitudes.

The absence of relatively dense air causes fireball characteristics to be substantially different from those of bursts at lower altitude. The fireball is an intensely hot and luminous mass, roughly spherical in shape, that appears immediately after detonation as the weapon residue incorporates material from the surrounding medium.

Also, the fraction of the explosive energy converted into blast and shock is less and decreases with increasing altitude; but the fraction of thermal energy increases with altitude. The fraction of the energy of explosion emitted as nuclear radiation is independent of height. The intensity of initial nuclear radiation reaching a point on the earth's surface is dependent on the amount of air through which it travels. For a point equal distance from two detonations, one at high-altitude and one lower, more initial radiation will be received from the high-altitude detonation, since there is less air in which it can be attenuated. Because of the wide dispersion of the fission products in a burst that takes place in the stratosphere, residual nuclear radiation is not a significant hazard.

1-4.3 Air Bursts

An air burst is one that occurs at an altitude of less than 100,000 feet but at such height that the fireball, at maximum brilliance, does not touch the surface of the earth.

The quantitative aspects of an air burst will depend upon the actual burst height as well as the yield of the weapon. The general phenomena will be much the same in all cases. Most of the shock energy will appear as blast with, generally, only a small portion transmitted as ground shock. Thermal radiation will be of sufficient intensity to cause severe burns and fires at relatively large distances. Initial nuclear radiation will also

penetrate long distances in the air; however, its intensity will decrease very rapidly with an increase in distance.

If the burst is moderately high, the residual nuclear radiation arising from the fission products will generally be of no consequence on the ground. If, however, the burst is of relatively low altitude, the fission products may fuse with debris from the earth's surface and part of this fused mixture may fall to earth at points near ground zero and in sufficient quantity to create a radiation hazard to living organisms.

1-4.4 Surface Bursts

A surface burst occurs when a weapon is detonated at or near the surface of the earth, or at such a height that the fireball makes contact with the surface.

Ground shock will be more pronounced than the air burst and will represent a larger portion of the total energy of shock. Of particular importance is the radiation hazard created by the enormous quantity of debris from the earth's surface which is fused with the fission products, and which results in a very widespread residual radiation hazard; i.e., "early fallout."

1-4.5 Subsurface Bursts

For general descriptive purposes, both underground and underwater bursts are considered as subsurface bursts. In such bursts, most of the shock energy will be transmitted through the subsurface medium, In cases where the detonation takes place at shallow depths, some of the shock energy may escape and be transmitted as air blast. Thermal and initial nuclear radiations will be absorbed within a short distance; but, again, for shallow depth bursts, some may escape to the air above. Residual nuclear radiation can be of significant consequence, since large quantities of the subsurface medium in the vicinity of the detonation will be contaminated with the radioactive fission products.

1-5 Characteristics of Nuclear Explosions

1-5.1 General

Characteristics usually associated with surface burst nuclear explosions are: the fireball, the atomic cloud, thermal radiation, air blast

and ground shock, crater, and nuclear radiation, Surface-burst conditions are of particular interest in this manual because of emphasis on the fallout, or residual nuclear radiation problem.

Although primary concern is with radiation effects, the other effects are of interest from the point of view of background information. This section offers a brief description of these effects.

1-5.2 The Fireball

Almost at the instant of a nuclear explosion, an intensely hot and luminous mass of air and gaseous weapon residue, roughly spherical in shape, is formed. The brilliance of this fireball is relatively independent of weapon yield. After about one millisecond it would appear, to an observer perhaps 50 or 60 miles away, on the order of 30 times more brilliant than the sun at noon.

Immediately after its formation, the fireball increases in size and engulfs more and more of the surrounding medium. As it increases in size, it decreases in temperature because of the increase in mass, and rises into the air in the manner of a hot-air balloon.

White the fireball is luminous, its interior temperature is at such a high level that all the weapon materials are in the vapor state. In a surface burst, where the fireball touches the earth's surface, the fireball will also contain enormous quantities of vaporized debris from the earth's surface. It is estimated, for example, that if only 5 percent of the energy of a 1 megaton explosion were spent in vaporizing material from the surface of the earth, about 20,000 tons of vaporized debris would be added to the normal constituents of the fireball. In addition, the strong afterwinds at the earth's surface will cause large quantities of debris to be sucked up as the fireball ascends.

1-5.3 The Atomic Cloud

As the fireball increases in size and cools, the included vapors condense to form a cloud containing solid particles of the bomb residue and debris and small water droplets. Its color is at first red to reddish brown, changing to white as further cooling takes place and condensation of large quantities of water occurs.

The speed with which the top of the cloud ascends depends on meteorological conditions as well as weapon characteristics. The eventual

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height to which it ascends is similarly dependent. Heights may be as high as 30 miles or more for large weapon yields. This maximum height is strongly influenced by the tropopause; i.e., the boundary between the troposphere below and the stratosphere above. When the cloud reaches the tropopause, it will spread out laterally.

The debris sucked up by the afterwinds into the cloud forms a visible stem, giving the characteristic mushroom shape to the atomic cloud.

1-5.4 Thermal Radiation

air and then re-emitted from the fireball as ultraviolet, visible, and infrared rays. Thus, thermal radiation that is of interest manifests itself in the form of heat and light.

The temperature at the interior of the fireball decreases steadily. The temperature at the surface of the fireball, curiously enough, decreases more rapidly for a small fraction of a second, then increases for a somewhat longer time after which it decreases steadily. Corresponding to the two pulses associated with the surface of the fireball, there are two pulses of emission of thermal radiation. The first pulse emits temperatures that are very high but of very short duration. Most of the radiations emitted during the first pulse are in the ultraviolet region. Although ultraviolet rays can cause skin burns, they are readily attenuated in air. Since the pulse is of such short duration, it may be disregarded as a source of skin burns. It is, however, capable of producing permanent or temporary damage to eyesight, particularly in individuals who may be looking in the direction of the explosion.

The second pulse, although it does not emit thermal radiation of as high a temperature as the first, lasts generally for several seconds and consists mostly of visible and infrared rays. It is this radiation that is the main hazard in producing skin burns, eye effects and fires.

For every kiloton weapon yield, about 330 billion calories of thermal radiation are released. This is equivalent to about 400,000 kilowatt-hours, and points out the important consequences that might be expected from thermal radiation.

Thermal radiation, like light, travels in a straight line and is readily attenuated by any opaque material. However, a shield that is merely placed between a target and the fireball and does not completely surround the target,

may not be entirely effective, particularly on a hazy day. Scattering of the thermal rays may cause them to reach a given point from all directions.

When thermal radiation impinges upon any object, part may be reflected, part absorbed, and part may pass through. That portion absorbed produces the heat that determines the damage. Dark objects will absorb and, consequently, transmit more heat than will light objects. Since the amount of energy from a nuclear explosion is high and is emitted in a very short time, it impinges upon objects with much intensity and heat is produced rapidly. Since only a small portion of the heat can be dissipated by conduction in the short time over which radiation falls upon the material, very high temperatures are generally confined to shallow depths. As a consequence, thin materials may flame, but thick materials may merely char.

A first-degree burn over a large portion of the body, characterized by redness of the skin as in sunburn, may produce a casualty. Second-degree burns, characterized by blistering, such as in severe sunburn, will usually incapacitate the victim if they are extensive. In third-degree burns, the full thickness of the ccur. skin is destroyed and if destruction is extensive enough. Loss of life can occur appreciation for the seriousness of thermal radiation, it should be observed that the potential for first-degree burns from a 1 megaton yield extends to a distance of about 15 miles. The potential for second-degree burns would extend to a distance of about 11 miles. A 1 megaton yield has the potential to ignite dry forest products, such as leaves, fine grass, and rotted wood, out to a distance of about 10 miles.

1-5.5 Blast

As the gases in the fireball expand rapidly outward, they push away the surrounding air with great force creating the destructive blast effects of the explosion. The front of the blast wave or shock front travels rapidly away from the fireball in all radial directions and behaves like a moving wall of compressed air. It travels roughly at the speed of sound and weakens with distance traveled from the point of detonation.

The pressure effects at a point some distance from the point of detonation are shown qualitatively by the pressure-time curve shown in Figure 1-1.

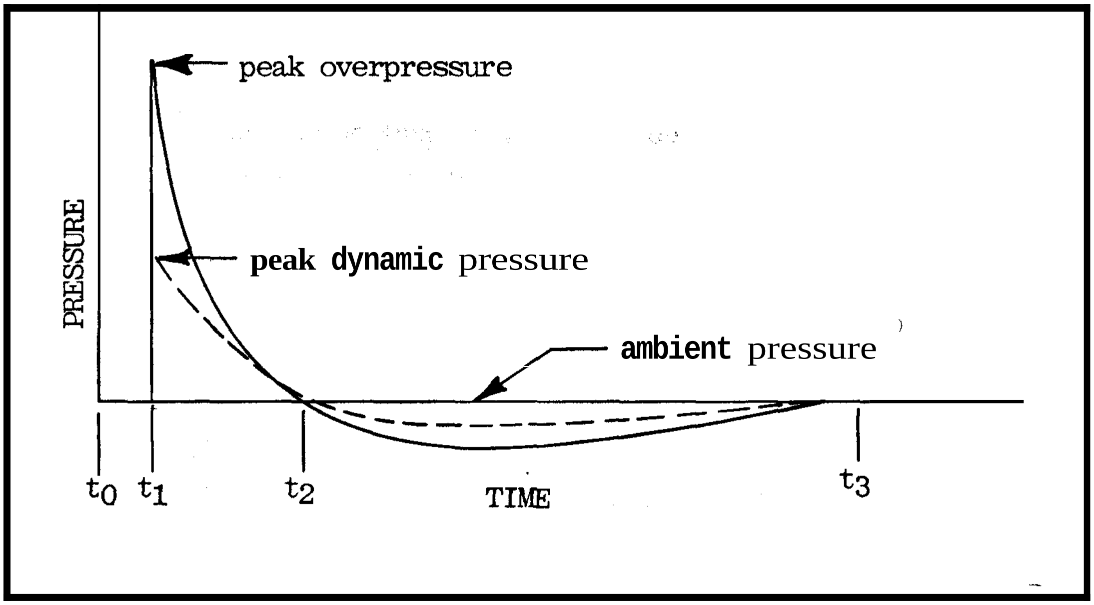

FIGURE 1-1

PRESSURE VS. TIME AT A POINT

At time t_0, the instant of the explosion, pressures at the point under consideration are at ambient atmospheric values and will remain so during the time necessary for the shock front to reach the point. When the shock front arrives at the location, pressures will increase virtually immediately to some peak values, magnitudes of which are primarily a function of weapon yield and distance from ground zero and, to a lesser extent, such parameters as atmospheric conditions. Time t_1 is the time at which the shock front reaches the fixed location.

Pressures are of two kinds, overpressures and dynamic pressures. Overpressures are pressures in excess of atmospheric values that may be likened to pressures that would be experienced by descent into depths of water. Dynamic pressures are the result of winds following immediately behind the shock front.

Both overpressure and dynamic pressure decay rapidly with time until, at time t_2, the overpressure has again reached the ambient value. The interval between times t_1 and t_2 is the time duration of the positive phase of the overpressures. The positive phase of the dynamic pressures, during which the winds blow away from the point of the explosion, persists for a slightly longer time than does that for the overpressures. Following the positive pressure phase, the fixed location is subjected to negative pressures in the time interval t_2 to t_3. During the negative phase, the point exists in a partial vacuum. The winds reverse in direction, blowing toward the point of detonation. Negative pressures are always substantially less than the peak pressures associated with the positive phase of the pressure diagram.

Most of the damage associated with the blast effect of nuclear weapons occurs during the positive phase of pressures. Overpressure or dynamic pressure or both may decide the extent of damage or establish the design loading criteria depending largely on structures type and location. For belowground structures, only the overpressures are of concern. An enclosed aboveground structure, with blast resistant walls and few openings, would be subject to the full effects of both the overpressures and the dynamic pressures. On the other hand, a structure designed with frangible walls would be reduced to a structural skeleton almost immediately; and the structural frame would be loaded primarily through the drag effect of the winds. The structural members of the frame would be completely surrounded by equal overpressures. Overpressures in the positive phase produce primarily a crushing effect, although translation effects also exist because of the time necessary for the overpressure wave to traverse the structure and engulf it. Dynamic pressures are essentially translational in effect.

Definite relationships exist between peak overpressure, weapon yield, distance from the explosion, arrival time, positive and negative phase duration, etc. To develop some appreciation for the magnitude of blast loading, it may be noted that a surface-burst 1-MT detonation would result in a peak overpressure of 100 psi at a distance of about 3500 feet. The peak dynamic pressure would be about 180 psi, resulting from winds of about 1600 mph velocity. There is a definite relationship between peak overpressure and the accompanying peak dynamic pressure. For peak overpressures above about 70 psi, the peak dynamic pressures will be higher than the peak overpressure. For overpressures below about 70 psi, dynamic pressures will peak at lower values than will overpressures. For example, a 1 MT surface burst weapon will produce a peak overpressure of 20 psi at a range of about 7000 feet. The accompanying peak dynamic pressure from winds of about 470 mph is about 8 psi.

Blast effects vary generally as the cube root of weapon yield. For example, a given peak overpressure would occur only three times as far from a 27-MT (=3x3x3) burst as from a 1-MT burst.

When the blast wave from an aboveground detonation reaches the surface of the earth, it is reflected back. Figure 1-2 shows four stages in the outward motion of the blast front. In the first and second stages, corresponding to times t_1 and t_2, the wave front has not yet reached the surface of the earth.

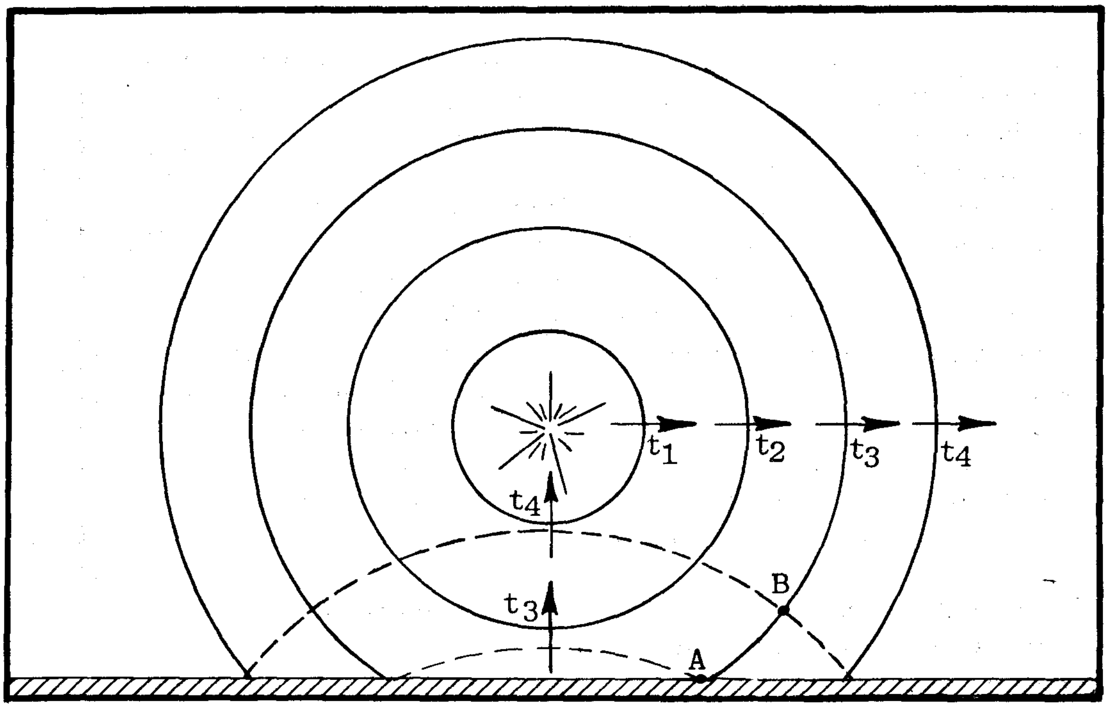

FIGURE 1 - 2

REFLECTION OF BLAST WAVE **AT EARTH'S** SURFACE

At time t_3, the incident wave has reached point A on the ground, and the reflected wave has also formed at point A. Point A is subject to a single shock with the total peak value of pressure the sum of those from the incident wave and the reflected wave. The point A may be considered as lying within the region of regular reflection; i.e. , where the incident and reflected waves do not merge except on the surface. Pressure will decay as shown in Figure 1-3a.

At time t_3, point B, in the air, is subjected to a shock from the incident wave. The peak value of overpressure begins immediately to decay in the normal way until , at time t_4, point B is subjected to a second shock from the reflected wave which has now reached that point. The peak pressure from the reflected wave adds to the residual from the incident wave. The combined pressures then decay in the normal way as depicted in Figure 1-3b. Point B also lies in the region of "regular" reflections.

Since the reflected wave travels in a hotter and more dense atmosphere than does the incident wave, it will move faster. Eventually, the reflected wave will overtake the incident wave and the two wave fronts will merge to produce a single front. This process of wave interaction is called "Mach" (or irregular) reflection. The region in which the two waves have merged is called the Mach (or irregular) region,in contrast to the regular region where merger has not taken place.

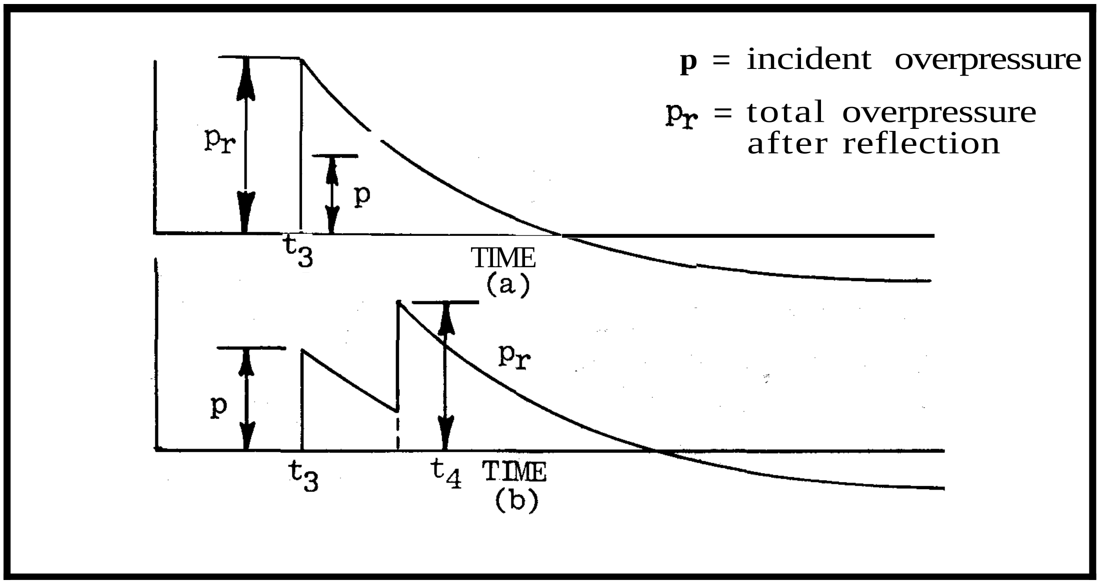

FIGURE 1 - 3

OVERPRESSURE VS. TIME
REGION OF REGULAR REFLECTION

Figure 1-4 shows several stages in the fusion of incident and reflected waves and the formation of the Mach stem. The intersection of the Mach stem, incident wave, and reflected wave, is called the triple point. It forms the so-called triple point path with outward motion of the blast wave. Below the path of the triple point, in the region of Mach reflection, only single pressure increases are experienced. This contrasts to points above the path in the region of regular reflections where two distinct shocks, a short time apart, are felt as first the incident and then the reflected wave reach a specific point-as, perhaps, the top of a high building or an aircraft. It is also of considerable importance to note that the Mach stem is essentially vertical. The accompanying blast wave is traveling in a horizontal direction at the surface and the transient winds are essentially parallel to ground. Thus, in the Mach region, blast forces on an aboveground structure are nearly horizontal and vertical surfaces are loaded more intensely than horizontal surfaces.

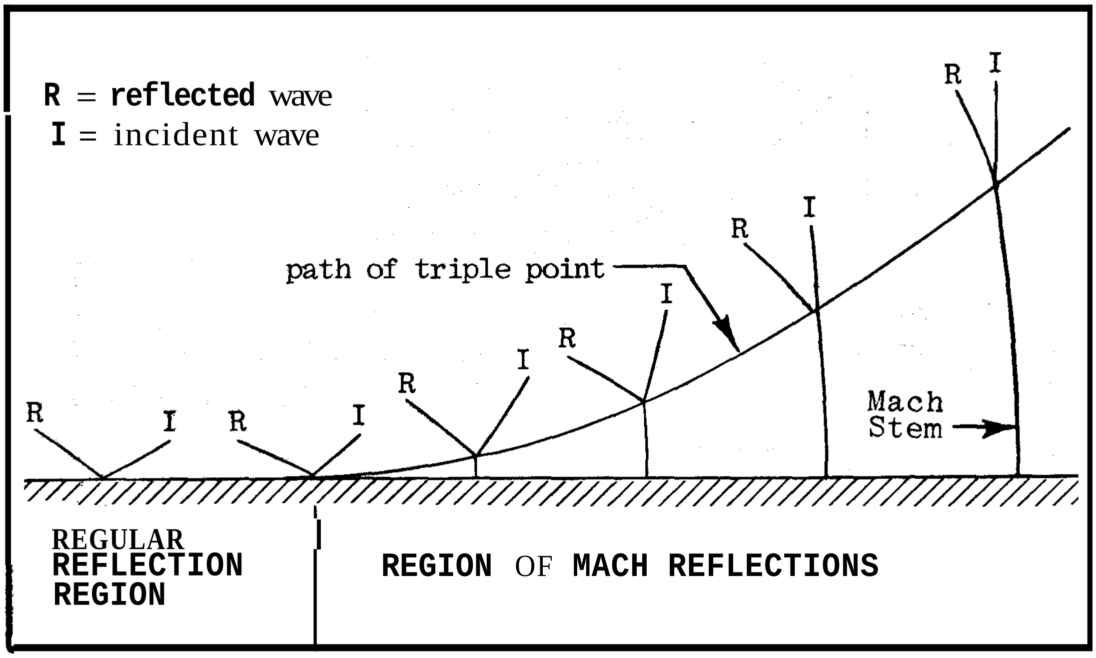

FIGURE 1-4

OUTWARD MOTION OF BLAST WAVE

Obviously, in a surface burst, only a single merged wave develops, and only one pressure increase will be experienced at all points on the ground or in the air.

It is impossible to describe structural damage that might be expected to occur as the result of blast without more or less complete knowledge of structural features and weapon characteristics, including yield and distance. For the purpose of this section, it is sufficient to consider the expected results from the standpoint of the types of construction that exist in typical American cities. More common structures are of brick and wood frame, multi-story masonry bearing, light steel frames, etc. For surface burst weapons, it would be expected that such construction would be destroyed within radii of 3 3/4 miles and 10 miles respectively for 1 megaton and 20 megaton explosions. Within this zone of complete destruction, peak overpressures would have ranged from about 3 psi at the edge to more than 1000 psi toward the center. Wind velocities would vary from about 150 mph at the edge to more than 2000 mph near the center. Within a band between 4.4 psi miles and 1.4 psi miles from a 1 MT explosion and

between **4.55** miles and **1.4** psi miles from a 20 MT explosion, damage would be **so** severe that extensive reconstruction would be required before the structures could be reused. Within this zone, overpressures would range from 1.5 to 5.0 psi and wind velocities from 50 to 150 mph.

Within a band between 1.4 and ***0.9*** psi miles from a 1 MT explosion and between 1.4 and 0.88 miles from a 20 MT explosion, overpressures would range between 1**.0** and 1.5 psi and maximum wind velocities from 33 to 51 mph. Moderate repairs would be required for most structures in this band.

Minor repairs would be required for most structures from 8 to **1/2** psi miles from a 1 MT detonation point and ~l/2 psi miles from a *20* MT explosion. Wind velocities at these distances would be about 20 mph maximum and peak overpressures about 0.5 psi. Overpressures of a magnitude of from one-quarter to one-half pound per square inch will shatter ordinary window glass. Overpressures of this magnitude have been observed at distances as great as 59 miles away from nominal-yield, test shots as the result of blast waves reflected out of the sky.

1-5.6 Craters

The size of the crater is a complex function of many things, including material, height of burst, and weapon yield. As an example of crater effects, a 1 MT weapon surface burst on dry soil would result in a crater about 630x2 feet in diameter and about 250' rock feet deep. Corresponding figures for a 20 MT explosion are 1680x2 feet and 815' feet.

The crater effect results partly from the vaporization of material, partly from consolidation, and partly from lateral translation and heave of material to form lips around the crater.

1-5.7 Electromagnetic Pulse

The electromagnetic pulse associated with nuclear explosions is complicated phenomenon which can only be discussed briefly here. The brief discussion here is intended only to acquaint the analyst with the phenomenon itself and its possible effects on installations of interest in certain nuclear defense areas.

The detonation of a nuclear weapon is accompanied by the immediate emission of high energy gamma rays, a form of nuclear radiation that will be discussed later.

This gamma radiation, as it penetrates into the atmosphere, interacts with molecules within the surrounding medium causing the expulsion of electrons from those molecules. These electrons move rapidly away from the point of detonation creating, in effect, a separation of electrical charges on a wholesale basis. A volume of positively charged molecules, defined by the spatial extent to which the gamma rays have penetrated, is surrounded by a volume with excess negative charge represented by the departed electrons. This relative displacement of positively and negatively charged regions produces an intense electric field giving rise to the phenomenon known as the electromagnetic pulse, EMP.

Distinctly different types of source regions are created depending upon whether the detonation is a surface burst or a high altitude or air burst. In the case of a surface burst, the source region in which the intense electromagnetic fields exist is limited by the atmosphere itself acting to severely reduce the extent to which gamma rays can penetrate. A typical low-yield surface burst may create a source region of the order of a mile in diameter. Increasing the weapon yield by a factor of one thousand will increase the diameter of the source region only by a factor of about three. Since, in surface bursts, the source region and damaging EMP are restricted substantially to high overpressure and thermal radiation areas, consideration of EMP, although important for hardened structures, is not of significant interest to public shelter systems which are designed primarily against fallout radiation outside the region of high intensity blast.

For high altitude bursts above the atmosphere, gamma rays can travel many miles without encountering air molecules. In such instances they will eventually affect the atmosphere over a vast region. For example, a high-yield weapon detonated just above the ionosphere may create a source region in the order of a thousand miles in diameter and perhaps as much as twenty miles thick. The source region is somewhat pancake in shape as opposed to the spherical shape from an atomospheric burst. Because of the great height of such a source region, the EMP radiated from it could appear over a substantial fraction of the earth's surface and be effective against regions that are unaffected by other nuclear effects. In such cases, the EMP could be damaging not only to power and hardened against all weapons effects but also to communications that are a part of the system of public shelter.

Whenever two opposite electrical charges are suddenly separated as they are in the source region, nearby charges are also subjected to a similar but somewhat diminished force or electric field. Thus, a portion of the electric field, moving away from the displaced charges at the velocity of light, can affect the position of other charges at great distances, and a strong

field can be created at some distance from the source region. These more distant fields are termed radiated fields, and this effect is called electromagnetic radiation. Electromagnetic radiation fields can cause charges to flow in distant but good conductors such as metallic structures, radio antennas or electrical wiring.

In the electromagnetic sense, the spectrum and waveform of EMP differ significantly from any other natural or man-made sources such as lightning or radio waves. The spectrum is broad, extending from extremely low frequencies into the UHF band. The waveform indicates a higher amplitude and much faster rise time than, for example, lightning. EMP is also widely distributed, as opposed to the localized effects of lightning.

Although there are vast differences between the phenomena of EMP and lightning, both can cause the same type of damage and an analogy between the two is useful for assessing the threat of EMP in terms of a familiar phenomenon. Most damage from EMP occurs as the energy in the form of strong electromagnetic fields is converted into very large currents and voltages when it impinges on cables or other conductors. Thus, like lightning, EMP can cause functional damage, such as the burnout or permanent electronic damage to components, or operational upset, such as the opening of circuit breakers or the erasure of storage in the memory bank of a computer.

It is this sort of potential damage that poses EMP as a serious threat that must be considered in the design of any civil or military defense facility that must maintain operational capability in the event of a nuclear disaster.

1-6 Study Questions and Problems

1. What is the basic difference in the manner in which energy is derived from conventional and nuclear explosions?

2. What is the approximate percentage distribution of the various types of energy released in a nuclear explosion?

3. What is the basic requirements for the explosive release of energy.

4. Describe the fission process.

5. What is the quantitative significance of a megaton explosion? a kiloton explosion?

6. Briefly describe the fusion process.

7. How is the fusion process triggered in a nuclear weapon?

8. On a weight of material basis, state the advantage of a fusion device over a fission device.

9. Distinguish between high-altitude, air, surface, and subsurface bursts.

10. Briefly define the fireball.

11. Describe the formation of the atomic cloud.

12. Describe the two-pulse phenomenon of thermal radiation, and explain why it is the second pulse that represents the most serious thermal hazard.

13. How can thermal radiation be guarded against?

14. Why is it that a shield, positioned between a target and a nuclear explosion, may not be completely effective in eliminating the thermal hazard?

15. What creates the blast wave in a nuclear explosion?

16. By means of a sketch, show the variation of overpressure with time at a point some distance removed from a nuclear explosion.

17. What are dynamic pressures, and how do they vary with time at a point some distance from an explosion?

18. During what phase of the pressures does most structural damage occur?

19. What is the approximate rule by which blast effects may be scaled with respect to weapon yield?

20. Describe the manner in which the Mach front is formed.

22. What is the "triple point"?

22. Describe the phenomena that gives rise to EMP.

23. What significant differences in the EMP threat can be expec ed from high altitude as opposed to surface burst detonations?

24. From the damage point of view, what threat is posed by EMP against civil and/or military defense facilities?

25. Why are protective measures such as employed for lightning not appropriate for protection against EMP?

CHAPTER II

NUCLEAR RADIATION AND FALLOUT

2-1 Introduction

In Chapter I, it was stated that one of the distinguishing features of a nuclear explosion is the delayed emission of about **15%** of the total energy yield of the weapon. This chapter will consider the nuclear radiation effects of nuclear weapons in somewhat greater detail than that accorded the other effects. There is no intent to minimize the importance of the latter. The intent is merely an emphasis on the former in keeping with the purpose of this publication.

2-2 Nuclear Radiation

2-2.1 General

In the fission process, there are many different ways in which the uranium or plutonium nuclei can be split up giving rise to several hundred fission fragments that are generally radioactive forms of lighter elements. Radioactivity associated with these fragments is usually manifested by the emission of beta particles and gamma radiation.

When a negatively charged beta particle is emitted, the nucleus of the radioisotope is changed into that of another element called a decay product. The decay products may also be radioactive and, in turn, decay with the emission of beta particles and gamma rays. About three stages of radioactivity are required for each fission fragment to reach a stable form. At any one time after the explosion, it is obvious that the fission product mixture will be very complex. Over 400 different isotopes of 37 light elements have been identified among the fission products.

Not all of the uranium or plutonium in a fission weapon undergoes fission. Both of these materials are, however, radioactive, and their activity consists in the emission of so-called alpha particles, gamma rays, and spontaneous fission. This activity must be considered in studying the radioactivity associated with nuclear weapons. Additionally, not all of the neutrons that are released in the fission process will interact with the fissionable constituents of the weapon and, thus, free neutrons must be considered as ionizing radiation associated with nuclear explosions when concerned with initial effects.

In fusion reactions, it is important to recognize that not all the products are radioactive fragments. Fusion reactions produce neutrons, and hydrogen and/or helium nuclei. Since an alpha particle is, in form, a helium nucleus, these particles, hydrogen and neutrons are the only forms of radioactivity associated directly with a fusion reaction. It must be recalled, however, that the triggering element of a fusion device is a fission reaction and that the free neutrons associated with a fusion reaction can be taken advantage of in producing further fussion.

2-2.2 Alpha Particles

Alpha particles are identical, in atomic structure, with the nuclei of helium atoms and because of their relatively large mass, they are very low in penetrating power. As a matter of fact, they can travel no more than about two inches in air before they are stopped, In any event, they are unable to penetrate even the lightest of clothing, and, consequently, they do not constitute a hazard so long as they are outside the body. If, however, uranium or plutonium enters the body in sufficient quantity by ingestion, inhalation or other means, the internal effects can be very serious. For this reason it is important in fallout shelters to insure that fallout particles which may be brought in on clothing or by other means are brushed off and disposed of in such a manner as to minimize the possibilities of ingestion with food or water and contact with personnel.

2-2.3 Beta Particles

Except for their origin and speed, beta particles are identical to the electrons that orbit about the nuclei of atoms. They originate in the nucleus of an atom, have a small mass relative to the atom and travel at high speed. A beta particle is somewhat more penetrating than an alpha particle but still not so penetrating as to constitute a consideration in structure shielding. Beta range in air is in the order of 10 to 12 feet. They are penetrating enough to produce radiation burns if they come in contact with exposed skin and are hazardous if they are ingested. The extent to which they are a hazard depends on, among other things, the energy and concentration of the B particles. The precautions mentioned with respect to alpha particles apply as welll to beta particles.

2-2.4 Gamma Rays

Gamma rays consist of streams of photons, small packets of energy, having no mass or electrical charge and traveling with the speed of light. They are quite similar to X-rays except for their origin. X-rays originate in the region of the orbiting electrons of an atom, whereas gamma rays originate in the nucleus and, in general, are somewhat higher in energy than are X-rays. They are

emitted in the fission process and in other secondary processes including decay of fission products.

Gamma rays are penetrating. They may travel in air for several hundred feet before interacting. Considerable mass of material is required to attenuate them. If they are absorbed by the body in sufficient quantity, either externally or internally, they constitute a very serious biological hazard. Gamma rays constitute the sole consideration in fallout shelter analysis. Structures used as protective shelter against their effect must have sufficient mass so oriented as to reduce their penetration and consequent effect on sheltered personnel to tolerable limits.

2-2.5 Neutrons

As stated earlier, neutrons are fundamental parts of the nucleus of an atom and may be released either in the fission or fusion process. They have a mass comparable to the proton and are neutrally charged.

Neutron shielding is a difficult problem different from that of shielding against gamma rays. It must be recalled that neutrons may be captured by nuclei of atoms to form new isotopes that are generally unstable and give off beta and gamma radiation. Neutrons do not cause ionization directly but, for the reason stated immediately before and as the result of other interactions, they may cause the emission of alpha, beta, and gamma radiation with the attendant biological hazard of ionization. Unreacted neutrons may undergo radioactive decay by beta emission.

As a matter of consequence is the fact that neutrons are not characteristic of radiation from fallout and are therefore not a consideration in fallout shelter analysis and design. They must, however, be considered in the design of shelters which protect against all of the effects of a nuclear detonation.

2-3 Initial Radiation

2-3.1 Initial vs. Residual Radiation

It is convenient for purposes of design of protective structures to consider nuclear radiation as divided into two categories, initial and residual; initial radiation is generally taken to be that which is emitted within the first minute of the explosion and residual radiation is that which is emitted following one minute after the detonation.

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The somewhat arbitrary time of one minute was originally based upon the fact that the radioactive cloud from a 20-kiloton explosion will reach a height of about 2 miles in 1 minute. The effective range of gamma rays in air is roughly 2 miles and, consequently, when the height of the cloud is greater, the effect of gamma radiation on the ground is no longer significant.

For higher weapon yields it still works out that one minute is realistic. The maximum distance over which gamma rays are effective will be greater for higher yields but so also is the rate at which the cloud will rise. A reverse situation exists for lower yields. The effective range is less as is the rate of ascent.

2-3.2 Importance of Initial Radiation

Because the effect of the initial nuclear radiation is confined to close-in locations, it becomes important in analysis and design only to a structure that is to survive close-in effects. These effects include blast pressures and thermal radiation as well as nuclear radiation. For such structures, consideration of initial nuclear radiation is important.

Fallout shelter is protective construction designed specifically to reduce the early fallout radiation hazard. No particular attention is given to blast and thermal effects although, as a matter of course and by slanting techniques, low levels of protection against these latter effects may be achieved.

2-4 Residual Radiation

Residual radiation is defined as that emitted later than one minute after the explosion. Direct neutron effects are confined to initial radiation, but alpha and beta particles and gamma rays constitute the radioactivity that is associated with residual radiation. This activity arises mainly from fission products and products of neutron reactions other than fission. The primary hazard from residual radiations stems from the creation of early fallout particles which incorporate the radioactive elements and may be dispersed over wide areas on the earth's surface.

2-5 Fallout

2-5.1 Formation

As stated previously, the tremendous heat generated in a nuclear explosion vaporizes the weapon residue. In addition, in the case of a surface burst, tons of debris from the earth's surface are sucked up into the fireball and, in

a vaporized or melted state, mingle with the vaporized radioactive fission products from the weapon. As the cloud ascends and cooling takes place, these vapors condense forming solid particles ranging in diameter from less than a micron (a micron is about 0.00004 inch) to several millimeters. This mixture will consist partly of particles that are comprised only of debris material from the earth, some that are a mixture of such debris and the radioactive fission products, and some that comprise condensed fission products. It is estimated that about 90% of the radioactivity involved is associated with particles in the head of the cloud and about 10% with those in the stem.

2-5.2 Quantity of Fission Products

The fission products from a nuclear detonation is a complex mixture of more than 400 different isotopes of some 35 elements most of which are radioactive. They decay by the emission of beta particles frequently accompanied by gamma rays. About 2 ounces of fission products are formed for each kiloton of fission weapon yield. The gamma ray activity of 2 ounces of fission products 1 minute after the explosion is roughly equivalent to that of 30,000 tons of radium. This, of course, decreases with time, but, if all the fission products from a one megaton explosion were to be uniformly spread over a plane surface of 5000 square miles, the radiation exposure rate at a level of 3 feet above the ground would still be 12 roentgens per hour after about 24 hours. As will be seen later, exposure to radiation of such intensity, even for a relatively short period of time, is extremely hazardous. Naturally, in an actual situation, the distribution of fallout will not be uniform, and higher levels of radiation may exist closer to the explosion than further out.

2-5.3 Early and Delayed Fallout

In article 2-5.1 it was pointed out that fallout particles range in size from less than a micron to several millimeters. Obviously the heavier particles will be deposited upon the earth relatively soon after the explosion while the very light ones will remain aloft for days,' months, or even years before they eventually settle out or are brought down with precipitation.

It is convenient to consider fallout as being divided into two parts, early and delayed. Early fallout is defined as that which returns to earth within a period of 24 hours following an explosion.

Delayed fallout, that which arrives after the first day, consists of the very fine, invisible particles which will accumulate in very low concentrations over a considerable portion of the surface of the earth. During the long time in which they are aloft, the process of decay materially reduces the intensity of

radiation that comes from them. This, together with the fact that they are widely dispersed, renders their effect as of no immediate danger to health, although there may be long time hazards that are not yet fully understood.

On the other hand, early fallout, arriving in heavy concentrations at early times while the intensity of radiation is still relatively high, represents an immediate, serious hazard to health and even life. Early fallout is the sole consideration in fallout shelters.

2-5.4 Distribution of Early Fallout

Factors affecting the distribution of early fallout particles include the height of the atomic cloud, quantity and size distribution of falllout particles, wind velocities and directions at various levels of the atmosphere through which the particles must fall, and the density of the atmosphere.

From the ever-changing pattern of parameters involved, it should be obvious that accurate predictions of fallout deposition are impossible. In general, it can be assumed that heavier concentrations will occur at points closer to ground zero and decreased concentrations as distances increase. Because of local variations in atmospheric conditions such as localized wind currents, up-drafts, etc, it is possible that "hot spots" may be encountered at distances where, normally, low concentrations might be expected.

For planning purposes, it is possible to plot, on the basis of assumed conditions, idealized fallout patterns that might be expected to develop following a detonation at a specific location. It is also possible to assume hypothetical attacks involving specific weapons detonated on specific targets at a particular time. From a study of these attack conditions in conjunction with observed weather parameters existing at that time, a generalized view of fallout distribution on an area-wide basis can be obtained. Such studies, covering a variety of attack situations under different weather conditions, have established that no part of the United States can be considered free of a potential fallout radiation hazard in the event of a nuclear attack.

Because fallout particles descend from the head of the atomic cloud, which may reach heights of over 30 miles, even for a surface burst, a point only far enough from the explosion to escape immediate effects may not receive any fallout at all for a period of as much as 30 minutes. This is an important factor from the standpoint of moving personnel to shelter and improvisation of shelter. Points further removed will not begin to receive fallout except after longer periods of time.

Once fallout begins to arrive, at a specific location, it may continue to fall for a period of several hours. It arrives, of course, in the form of solid particles, visible, and with an average size on the order of that of fine beach sand, Being relatively heavy, it tends to remain where it is deposited except under exceptional wind conditions which may cause some drifting. Its deposition is consequently fairly uniform. All of the early fallout, which would result in a biological hazard, would be deposited somewhere, within a period of 24 hours from the explosion. The area affected by significant amounts of fallout from a single explosion could be several thousand square miles in extent.

2-6 Measurement of Radioactivity

2-6.1 The Roentgen

The unit generally used to express exposure to gamma radiation is the roentgen. A roentgen is defined as the quantity of gamma radiation which will give rise to the formation of 2.08×10^9 ion pairs per cubic centimeter of dry air at standard temperature and pressure. The interaction of gamma rays with matters results in ionization, or the production of ion pairs. There are relationships between the exposure of gamma radiation in roentgens and the biological effect that might be expected. The roentgen, then, may be considered a unit measure that can be used to relate the radiation hazard from fallout to its biological effect on human beings. It is in this sense that it is used as a unit of measure in fallout shelter analysis.

2-6.2 Dose Rate and Dose

Dose rate, for the purpose of this publication, is the rate at which radiation is being received from the field of contamination, by a detecting device that measures radiation being received from all spherical directions. The unit of measure is roentgens per hour. The reference dose rate is that which would exist one hour after the explosion. If the dose rate is known at any time after fallout has ceased to arrive, the reference dose rate can be determined and, from this, the dose rate at any other time can be predicted.

For various reasons, it is impossible to predict, with any degree of accuracy, the dose rate that might be expected at a specific location. For planning and study purposes, it has sometimes been assumed that initial dose rates in areas of heavy, medium and light concentrations of fallout are 10,000, 1,000, and 200 roentgens per hour respectively.

Dose, or total dose, is the integrated dose rate with respect to time. It is the quantity of radiation, expressed in roentgens, to which a point or body would be subjected in a given period of time. Total dose can be related to expected average biological effects.

2-7 Dose and Dose Rate Calculations

2-7.1 Decay of Radioactivity

The half-life of a radioactive isotope is the time required for the radioactivity to decrease by one half from any initial value. In the fission products from a nuclear detonation, the many isotopes involved have half-lives ranging from a fraction of a second to milleniums. As a consequence, a study of the rate at which radioactivity from fallout decays must be considered from the standpoint of an average product containing representative fractions of all isotopes involved.

The rate of decay can be expressed by the following equation plotted in Figure 2-1.

$$d_1 = dt^{1.2}$$

where:

d_1 = dose rate at H + 1 hr. (H = time of explosion)

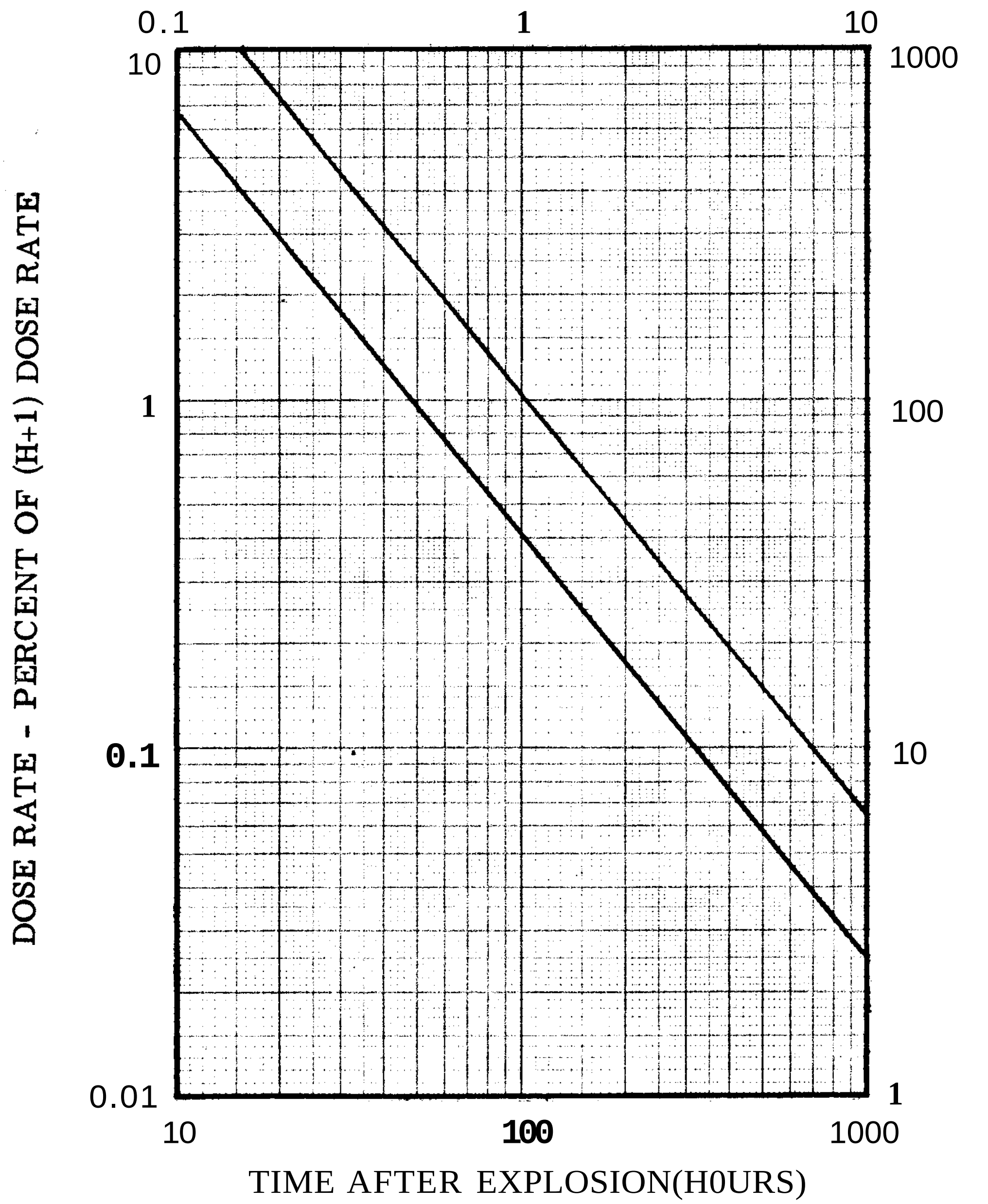
d = dose rate at time t,

t = time (hours) after detonation.

A more approximate rule, which gives a more immediate appreciation of the rate of decay, is the so-called Seven-Ten rule. For every seven-fold increase in time after the explosion, there is a ten-fold decrease in dose rate. As an example, if the reference dose rate at H + 1 hrs. is taken as 1000 roentgens per hours, seven hours after the explosion the dose rate would be 100 roentgens per hour. Forty-nine hours, about 2 days, after the explosion the dose rate would be 10 roentgens per hour and 2 weeks after the explosion it would be 1 roentgen per hour.

2-7.2 Accumulated Dose

Based on the dose rate equation given in section 2-7.1, the following expression will yield the total accumulated dose to which an exposed point or



'or times from 0.1 to 10 hours, use upper curve and read to right
'or times more than 10 hours, use lower curve and read to left.

FIGURE 2-1

APPROXIMATE RATE OF DECAY
OF RADIOACTIVITY FROM FALLOUT

body will be subjected in a given time interval.

$$D = 5\, d_1 \left(t_i^{-0.2} - t_f^{-0.2}\right)$$

In this expression

D = dose accumulated from t_1 to t_f

t_i = time of initial exposure

t_f = time of final exposure

Table **2-1** is given as an aid for solving dose and *dose* rate problems, With the aid of the data given in the table, it is observed that the total accumulated dose to infinite time is 5 times the initial dose rate at H+ 1 hours. Of this possible total, *a* point or body would accumulate about 40% after 12 hours, 50% after 30 hours, 60% after 4 days and 70% after 2 weeks. As will be seen in subsequent paragraphs, doses absorbed in short periods of time are of extreme importance in determining the expected biological effect.

2-7.3 Example Problems

1. At a point some distance from a nuclear explosion, fallout begins to arrive at H + 4 hours and continues to fall for **8** hours. After it has ceased to fall, an observation indicates a dose rate of 50 roentgens per hour. What will the dose rate be at this location **2** days after the detonation?

Solution: (data from Table **2-1)**

$$d_1 = dt^{1.2} = 50\ (12)^{1.2} = 50\ (19.73) = 986 \text{ R/hr.}$$

$$d = d_1 \div t^{1.2} = 986 \div (48)^{1.2} = (986) \div (0.0096) = 9.5 \text{ R/hr.}$$

2. Twenty hours after a detonation, the observed dose rate is *120* R/hr. A civil defense team is sent on a mission *90* hours after the detonation and remains for 5 hours. What total dose will be accumulated by the members of the team during the *5* hours on the mission?

Solution: (data from Table **2-1)**

$$d_1 = dt^{1.2} = 120\ (20)^{1.2} = 120\ (36.41) = 4370 \text{ R/hr.}$$

TABLE 2-1

VALUES FOR DOSE AND DOSERATE FORMULAS

t (hrs.)	$t^{1.2}$	$t^{-0.2}$	t (hrs	$t^{1.2}$	$t^{-0.2}$
0.1	0.063	1.586	25	47.59	0.525
0.2	0.145	1.381	26	49.89	0.521
0.3	0.236	1.273	27	52.20	0.518
0.4	0.333	1.202	28	54.52	0.514
0.5	0.435	1.149	29	56.87	0.510
0.6	0.542	1.110	30	59.23	0.505
0.7	0.652	1.074	32	64.00	0.500
0.8	0.765	1.046	34	68.83	0.494
0.9	0.881	1.023	36	73.72	0.488
1.0	1.000	1.000	38	78.66	0.483
1.5	1.627	0.921	40	83.67	0.478
2.0	2.300	0.871	42	88.70	0.474
2.5	3.003	0.826	44	93.79	0.470
3.0	3.737	0.803	46	98.93	0.465
4.0	5.278	0.756	48	104.1	0.461
5.0	6.899	0.725	50	109.3	0.457
6.0	8.586	0.697	55	122.6	0.449
7.0	10.33	0.679	60	136.1	0.441
8.0	12.13	0.660	65	149.8	0.434
9.0	13.96	0.644	70	163.7	0.427
10.0	15.85	0.631	75	177.8	0.422
11.0	17.77	0.619	80	192.2	0.417
12.0	19.73	0.608	85	206.7	0.412
13.0	21.71	0.599	90	226.5	0.407
14.0	23.74	0.590	95	236.2	0.402
15.0	25.78	0.582	100	251.2	0.399
16.0	27.86	0.574	120	312.6	0.384
17.0	29.28	0.567	140	376.2	0.372
18.0	32.09	0.560	160	442.5	0.362
19.0	34.23	0.555	180	508.5	0.354
20.0	36.41	0.550	200	577.1	0.347
21.0	38.61	0.544	250	754.3	0.333
22.0	40.82	0.539	300	938.7	0.319
23.0	43.06	0.534	336	1075.	0.313
24.0	45.31	0.530	720	2683.	0.268

$$D = 5d_1\ (t_i^{-0.2} - t_f^{-0.2}) = (5)(4370)(0.407-0.402) = 109\ R.$$

3. It has been determined that the H + 1 reference dose rate in an area is 1000 R/hr. If a rescue team enters the area 2 days after the detonation, how long may it remain if the accumulated dose is not to exceed 60R?

Solution: (data from Table 2-1)

$$D = 60R = 5d_1\ (t_i^{-0.2} - t_f^{-0.2}) = 5000\ (.461 - t_f^{-0.2})$$

$$5000\ (t_f^{-0.2}) = 2305 - 60 = 2245$$

$$t_f^{-0.2} = .449;\ t_f = 55\ \text{hrs.}$$

$$\text{stay-time} = 55-48 = 7\ \text{hrs.}$$

2-8 Biological Effects of Gamma Radiation

2-8.1 General

Exposure to ionizing radiation, such as alpha and beta particles and gamma rays, has long been known to present a hazard to living organisms. As the result of ionization, some of the constituents, essential to the normal functioning of cells, may be altered or destroyed. Products formed may act as poisons. The action of ionization may result in breaking of the chromosones, increasing the permeability of cell membranes, destruction of cells, and inhibition of mitosis, the process of cell division necessary for normal cell replacement in living organisms. Such cell changes may seriously alter body functions when enough cells are affected to reduce the total function of the organs made up of such cells.

2-8.2 Acute vs. Chronic Doses

Because of the difference in biological effect, it is necessary to distinguish between an acute (short-term) exposure and a chronic (extended) exposure. It is not possible to precisely differentiate between the two but an acute dose may be taken for purposes of injury evaluation, as one incurred over a period of from 2 to 4 days. Although radiation from fallout persists over a long time, it is during the first few days that the dose rate is relatively high and the possible exposure more intense.

The distinction between acute and chronic doses is important because of the fact that, for doses not too large, the body can achieve partial recovery from some of the radiation injury while it is still exposed. Thus, a larger total radiation dose would be required to produce a given degree of injury, if the dose is spread over a long period of time, than would be required were the dose received in a very short period.

2-8.3 Pathology of Radiation Injury

Radiation damage results from changes induced in individual cells. Cells of different types and organs have different degrees of sensitivity to radiation. Such sensitivity decreases in the following order: lymphoid tissue and bone marrow; testes and ovaries; skin and hair; blood vessels; smooth muscle; and nerve cells. The list of items included in the above order are by no means complete.

When living tissue is exposed to radiation, lymphoid cells are destroyed and disintegrate; and, lymph glands waste away with a resultant impairment of the production of lymphocytes, necessary to the function of the gland. A rapid disappearance of lymphocytes implies certain death if such disappearance is almost complete. A study of radiation casualties in Japan showed, commonly, the wasting away of lymph nodes, tonsils, appendices and spleens.

Except for lymphocytes, all other formed blood cells arise from the bone marrow. Under normal circumstances, these cells leave the marrow and enter the blood stream where they remain until they are naturally destroyed or are killed in defense of infection. Bone marrow shows remarkable changes when irradiated. There is an immediate temporary cessation of cell division and the marrow becomes depleted of adult forms of cells and, barring regeneration, progressively wastes away. Such extreme atrophy (wasting away) of the bone marrow was common among those dying of radiation injury in Japan.

Morphologic changes in the human reproductive organs, compatible with sterility, are thought to occur with acute doses of from 450 to 600 roentgens. (Acute doses of such a quantity could result in death.) Temporary sterility was found among surviving men and women in Japan, but many have since produced normal children. The testes are apparently quite radiosensitive. Changes in the ovaries are less striking. Some Japanese women suffered menstrual irregularities, miscarriages and premature births. There was an apparent increase in the death rate of pregnant women.

Epilation, the loss of hair, was common amcrng Japanese victims. In severely exposed but surviving cases, hair began to return after a few months.

Eyebrows, eyelashes and beards apparently were more resistant than hair on other parts of the body.

Ulcerations of intestinal linings were noted in Japanese victims. Acid-secreting cells of the stomach are lost. Mitosis stops in the intestinal glands. Bacterial invasions occur and ulcers may become fecally contaminated. Since white blood cells are simultaneously depleted and infection cannot be combated, such intestinal ulcerations become points of entry for bacteria that may kill the victim.

Hemorrhage is common after radiation exposure. This results from the depletion of blood platelets necessary for clotting. Often such hemorrhages are so widespread that severe anemia and death are the result.

The loss of protective coverings of tissues, white blood cells, and antibodies lowers the resistance of the body to bacterial and viral infections, and a patient may die of infection even from bacteria that are normally harmless. Thus, casualties may result not only directly from radiation affects but also indirectly because of the effect of radiation in impairing the normal life sustaining functions of the body organs.

2-8.4 Natural Radiation Doses

The human body is continually exposed to nuclear radiation from various sources. These are chronic exposures spread over the lifetime of the individual. Certain naturally occurring radioactive substances are present in **all** soil and rock. Cosmic rays, originating in space, contribute to the total dose of background radiation naturally received. During an average lifetime, every human being absorbs a total dose of about 10 roentgens from natural sources.

In addition to radiation from natural sources, the human body may be exposed to further dosages from chest and dental x-rays, luminous wrist watch dials, viewing of television, etc. People engaged in occupations involving peaceful, as well as military, applications of nuclear energy are exposed to doses over and above those experienced by others. Such exposures are very carefully controlled by appropriate safeguard regulations and result in no appreciable risk to the individuals involved. Exposures from the delayed fallout from weapons testing has added to the total exposure normally received, but the amount received from this source has, to date, been very minute compared even to natural background radiation.

Even though the chronic dosages from the sources enumerated above are small in magnitude, it is nevertheless, probably true that radiation, even at a

low dose level, may have indeterminable long range deleterious effects, and, aggravated exposure, even though it may not be of immediate consequence, could be harmful.

2-8.5 Clinical Features of Acute Radiation Injury

All that is known quantitatively about the immediate effects of various radiations on humans comes from analysis of experience with radiation therapy of patients, from studies of accidental radiation exposures, and from the study of Japanese exposed to atomic bomb radiation.

Classification of Radiation Injury

The following is a description of some effects that could be expected as a result of an acute whole-body exposure from fallout radiation, i.e., that received over a period of up to two to four days.

Asymptomatic Radiation Injury

This class of injury, not apparent to the victim and undetectable by the physician, occurs after brief exposure of less than 50R. The effects of an exposure of less than 50R on blood cells can be detected only in retrospect by statistical analysis of the blood cell counts or chromosomes of cells obtained from a large group of exposed people. Clinically, some normal persons irradiated in this dose range will show mils signs and symptoms of gastrointestinal distress, such as loss of appetite and nausea, easily confused with the effects of anxiety and fear.

Acute Radiation Syndrome

This class of radiation injury may be caused by radiation of the whole body or major portions of the torso or head. Clinical manifestations of the acute radiation syndrome include general "toxic" symptoms, such as weakness, nausea, vomiting, and easy fatigue, and specific symptoms and signs caused by damage to the gastrointestinal tract, the blood-forming organs and the central nervous system. The signs of systemic radiation damage include loss of hair (epilation) and a tendency to bleed easily.

Five clinical levels of severity of acute radiation effects are distinguished and correlated with the size of the exposure:

Level I: Whole-body exposures in the range of 50-200R. Less than half the persons exposed experience nausea and vomit within 24 hours. There are either no subsequent symptoms or, at most, only increased fatigability. [Fewer than 5 percent (1 out of 20) require medical care for their gastric distress.]

All can perform tasks, even when sick. Any deaths that occur subsequently are due to complications such as intercurrent infections, debilitatingdiseases, and traumatic injuries such as those from blast and thermal burns.

Level II: Whole-body exposures in the range of 200-450R. More than half of this group experience nausea and vomit soon after the onset of exposure and are ill for a few days. This acute illness if followed by a period of 1-3 weeks when there are few if any symptoms. At the end of this latent period, epilation (loss of hair) is seen in more than half; a moderately severe illness develops, due primarily to infection often characterized by sore throat and to loss of defensive white blood cells resulting from damage to the blood-forming organs. Most of the people in this group require medical care. More than half will survive without therapy, and the chances of survival are better for those who received the smaller doses and improved for those receiving medical care.

Level III: Whole-body exposures in excess of 450R (450R to 900R). This is a more serious degree of the illness described for Level II. The initial period of acute gastric distress is more severe and prolonged. The latent period is shortened to one or two weeks. The main episode of illness is characterized by extensive oral, pharyngeal, and dermal hemorrhages. Infections such as sore throat, pneumonia and enteritis, are commonplace. People in this group need intensive medical care and hospitalization to survive. Fewer than half will survive in spite of the best care, with the chances of survival being poorest for those who received the largest exposures.

Level IV: Whole-body exposures in excess of 600R (600R to 1,000R). This is an accelerated version of the illness described for Level III All in this group begin to vomit soon after the onset of exposure. Without medication this gastric distress can continue for several days or until death. Damage to the gastrointestinal tract is the predominant lesion. It is manifested by intense cramps and an intractable diarrhea, which usually becomes bloody. Death can occur anytime during the second week without the appearance of hemorrhage or epilation. All persons in this group require care for or relief of the gastrointestinal symptoms, but it is unlikely even with extensive medical care that many can survive. During a protracted exposure to this amount of gamma radiation, it is unlikely that this type of gastrointestinal distress would be the first evidence of injury. What little clinical evidence exists indicates that any clinical problems resulting from this exposure at a low rate would be related to failure of the bone marrow.

Level V: Whole-body exposures in excess of several thousand R. This level is an extremely severe illness in which hypotensive shock secondary to vascular damage predominates. Symptoms and signs of rapidly progressing shock come on almost as soon as the dose has been received. Death occurs within a few days.

2-8.6 Recovery From Radiation Effects

If, over a period of a few days, a person is exposed to a dose of less than about 200 roentgens, he should not become incapacitated nor should his ability to work be seriously affected. If the dose exceeds about 200 roentgens, persons so exposed will suffer increasing radiation sickness with increasing dosage and the probability of death is extremely high if the dose absorbed exceeds 600 roentgens.

The human body has the capability of repairing a major portion of radiation injury, except in cases where the dose is so great that death occurs within a period of up to several weeks. On this account, individuals can survive large amounts of radiation if the exposure is spread over a period of time long enough to allow the recuperative processes to take place.

In determining the probable biological effect of exposure to radiation it may be assumed that about 10% of the exposure causes irreparable damage or is, in a sense, irrecoverable. About one-half of the remainder can be assumed to be recoverable in about a month and the other half after about three additional months. The equivalent residual dose (ERD) at any time is then equal to *10%* of the accumulated dose plus the balance of the accumulated dose that has not yet been recovered or repaired.

If it is assumed that the recovery begins about four days after the onset of exposure and that repair occurs at the rate of 2.5% of the recoverable portion per day, the ERD can be expressed mathematically as follows:

$$ERD = 0.1D + 0.9D(0.975)^{t-4}$$

In the above expression, D is a single day dose and t is the number of days from the onset of exposure to the time at which the ERD is to be computed. Table 2-2 gives powers of ***0.975*** as an aid in the solution of the above equation.

As an example of the use of the above expression, let it be assumed that a group of civil defense workers have been exposed to doses of 40, 25, and 15 roentgens each on three consecutive days. About 15 days after the first exposure this group is needed to carry out another emergency mission in a fallout area. What additional dose can the group tolerate on mission if their total ERD is not to exceed 100 roentgens?

Solution: (data from Table 2-2)

$$ERD = 0.1D + 0.9D(0.975)^{t-4}$$

$$ERD(1) = 0.1(40) + 0.9(40)(0.975)^{11} = 4.0 + 27.4 = 31.4$$

$$ERD(2) = 0.1(25) + 0.9(25)(0.975)^{10} = 2.5 + 17.6 = 20.1$$

$$ERD(3) = 0.1(15) + 0.9(15)(0.975)^{9} = 1.5 + 10.8 = 12.3$$

The total ERD at the beginning of the mission is thus about 64 roentgens and the team can be exposed to an additional 36 roentgens on the mission. It is noted that, of the 80 roentgen dose accumulated prior to the mission, 8 roentgens *are* irrecoverable and, of the remaining 72 roentgens, about 16 roentgens have been recovered prior to the mission.

2-8.7 Late Effects

Some consequences of exposure to relatively large doses of nuclear radiation may not become apparent except after several years from exposure. These effects might include some malformations in the offspring of those exposed, the formation of cataracts, shortening of the life span, leukemia and other forms of malignancy and the retarded development of children in the uterus at the time of exposure. Although many theories have been advanced for the causes of these late effects, the entire matter *is* largely in the realm of the unknown.

TABLE 2-2

POWERS OF 0.975

Power	Value	Power	Value	Power	Value
1	0. 98	15	0.68	38	0.38
2	0. 95	16	0.67	40	0.36
3	0. 93	17	0,65	45	0.32
4	0. 90	18	0.63	50	0.28
5	0,88	19	0,62	55	0.25
6	0.86	20	0,60	60	0.22
7	0.84	22	0.57	65	0019
8	0.82	24	0. 54	70	0.17
9	0.80	26	0.52	80	0.13
10	0. 78	28	0,49	90	0.10
11	0. 76	30	0.47	100	0.08
12	0. 74	32	0.44	110	0.06
13	0.72	34	0.42	120	0.05
14	0. 70	36	0.40		

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2-9 Study Questions and Problems

1. In the fission process, what is the predominant feature of the fission fragments that are formed?

2. How is radioactivity, associated with fission fragments, usually manifested?

3. What is meant by "decay product"?

4. Apart from beta particles and gamma rays, what other forms of radioactivity are associated with nuclear explosions, and what are their sources?

5. What is an alpha particle?

6. Why are alpha particles not a consideration in shielding?

7. What is the major danger associated with alpha particles?

8. What is the difference between a beta particle and an electron?

9. What is the major hazard associated with beta particles, and why are they not a consideration in shielding?

10. Of what do gamma rays consist?

11. Compare gamma rays to X-rays.

12. What is the importance of gamma radiation in shielding considerations?

13. Why are neutrons not a consideration in fallout shelters?

14. Distinguish between initial and residual radiation.

15. What is the significance of the one-minute time as the dividing line between initial and residual radiation?

16. Under what conditions of analysis and design is initial radiation important?

17. Why is initial radiation not normally considered in fallout shelters?

18. From what does the primary hazard from residual radiations stem?

19. Tell how fallout is formed.

20. Describe nuclear fa1lout.

21. How much fission product (approximately) is formed for each kiloton of fission yield?

22. Since fusion reactions do not produce radioactive fragments, why is there a fallout problem associated with such weapons?

23. Distinguish between early and delayed fallout.

24. What are the considerations that minimize the hazard associated with delayed fallout?

25. Describe the manner in which early fallout is distributed and the factors that influence its distribution.

26. Why is it impossible to accurately predict the deposition of fallout?

27. Many uninformed people consider that fallout causes the air, even in a shelter, to be unfit to breath. Comment on this.

20. On an areawide basis, comment on the relative hazards from thermal, blast and radiation effects.

29. What is the significance of the roentgen as a unit of measure in the radiation hazard? (Note: the instructor may wish to introduce other units of measure used for the same purpose.)

30. Define dose rate.

31. What is meant by the term "reference dose rate"?

32. Distinguish between dose and dose rate.

33. What initial dose rates may be expected in areas of heavy, medium, and light fallout deposition?

34. What is meant by half-life of a radioactive isotope?

35. Explain the Seven-Ten Rule for describing the approximate rate of decay of fallout radiation.

36. In terms of initial dose rate, what is the approximate accumulated dose to infinite time?

37. At a point some distance from an explosion, fallout begins to arrive at H + 6 hours and continues to fall for 10 hours. After it has ceased to fall, an observation indicates a dose rate of 25R/hr. What will the dose rate be at this location at H + 4 days?

38. Forty-eight hours after a detonation, the observed dose rate is 80R/hr. A rescue team is sent on a mission 4 days after detonation and remains for 8 hours. What total dose will the team accumulate during the 8-hour mission'

39. It has been determined that the H + 1 hour reference dose rate in an area is 500R/hr. A rescue team enters the area 4 days after detonation. How long may it remain in the area if the accumulated dose over the stay time is not to exceed 40R?

40. The reference dose rate in a disaster area is 1000R/hr and in an emergency operating center in the area it is 10R/hr. A rescue team has spent 48 hours in the shelter and is to be sent on a mission in the area. How long can it remain if the total accumulated dose, including that accumulated in the shelter, is not to exceed 20R?

41. What effect does ionizing radiation have on living organisms?

42. Distinguish between the biological effects from acute and chronic doses of radiation.

43. Briefly discuss the pathology of radiation injury.

44. What effects may be expected as the result of whole body exposure to acute doses of 50R? 150R? 250R? 450R? 800R? 5000R?

45. What is meant by the term "equivalent residual dose"?

46. Why can the human body survive large amounts of radiation if such doses are spread over a long period of time?

47. A civil defense rescue team has been exposed to doses of 30, 20, 10 and 15 roentgens each on four consecutive days. About twelve days after the first exposure, this group is needed on another emergency mission in a fallout area. What additional dose can be tolerated if the total ERD is not to exceed 100R?

48. Comment on the myth that radiation sickness is communicable.

49. What precautions should be observed with regard to the intake of food and water that has been subjected to nuclear fallout?

CHAPTER III

BASIC CONCEPTS IN FALLOUT RADIATION SHIELDING

3-1 Introduction

The radioactivity associated with the fission products included in the early fallout from a nuclear surface burst manifests itself in the form of alpha and beta particles and gamma rays. Alpha and beta particles, although biologically dangerous if ingested or inhaled, or if they impinge upon exposed portions of the body, are almost completely attenuated by relatively light weight shields such as clothing. As a consequence, alpha and beta particles are not considered in fallout shielding problems. Gamma radiation, on the other hand, is not readily attenuated and is biologically destructive. It constitutes the sole consideration involved in shielding problems associated with fallout shelters.

Exposure to large acute doses of gamma radiation can result in serious illness or death to humans. The level of radiation that could be absorbed by unprotected individuals in areas of relatively light fallout contamination could also be lethal. It is the purpose of fallout shelters to minimize, to the extent practical, the biologically hazardous effects of gamma radiation from nuclear fallout. Fallout shelter analysis involves the calculation of the degree of radiation protection afforded by a shelter to its occupants. To make the fallout shielding methodology and calculations more meaningful, certain basic concepts of radiation shielding are discussed in simplified terms. A clear understanding of these basic concepts is essential to a fallout shelter analyst.

The shielding procedure described in this text is officially designated as the "DCPA Standard Method for Fallout Gamma Radiation Shielding Analysis, and throughout the text is simply designated as the "Standard Method.

Basic data and primary calculations underlying the Standard Method were developed by L. V. Spencer and published in Structure Shielding Against Fallout Radiation From Nuclear Weapons, NBS Monograph 42 June 1962 (U.S. Government Printing Office, Washington, D.C.). The standard method was developed, from the work of Spencer, by Charles Eisenhauer of the National Bureau of Standards and Neal FitzSimons of the Defense Civil Preparedness Agency and was first published as Design

and Review of Structures for Protection from Fallout Gamma Radiation. An Engineering Method for Calculating Protection Afforded by Structures Against Fallout Radiation. NBS Monograph 76, July 2, 1964 (U.S. Government Printing Office, Washington, D. C.) by Charles Eisenhauer discusses the assumptions and the reasoning by which the calculations were derived from the basic data of NBS Monograph 42. Although the work of others has resulted in continuing refinement to the Standard Method, these three references serve as the basic foundation for this text, and occasional reference will be made to the material of this and following chapters.

3-2 Radiation Emergent From a Barrier

In Figure 3-1, a point source of radiation emits gamma radiation in all directions. Gamma radiation consists of continuous streams of photons, packets of energy without mass, that travel in straight lines from their source, the nuclei of radioactive isotopes, until they interact with electrons of obstructing atoms.

Any one of several things might happen to a photon that is incident upon a barrier, as illustrated in Figure 3-1. it may pass through the barrier without an interaction taking place, in which case it is termed direct radiation. It may interact with an orbital electron of an atom in the barrier and lose all of its energy to that electron through photoelectric absorption, in which case it is termed absorbed radiation. As a third case, a photon may interact with an orbital electron without losing all of its energy, and a new photon with lower energy will depart in a different direction. This is the Compton Scattering. The departing photon is termed scattered radiation. Scattering can take place in the air or in the barrier as indicated in the figure. As the result of a scattering interaction, the new photon may emerge from the same face of the barrier upon which the original photon was incident. This is termed back-scattered radiation.

There is a correlation between the energy loss and the angle of deflection that accompanies a scattering interaction. Gamma radiation that has undergone large changes in direction is apt to be much lower in energy than unscattered gamma rays. This is particularly true when the direction change is the result of several interactions. As energy is lost with each successive scattering, the chance of absorption becomes increasingly greater, since photoelectric absorption is more prevalent at lower gamma ray energy levels.

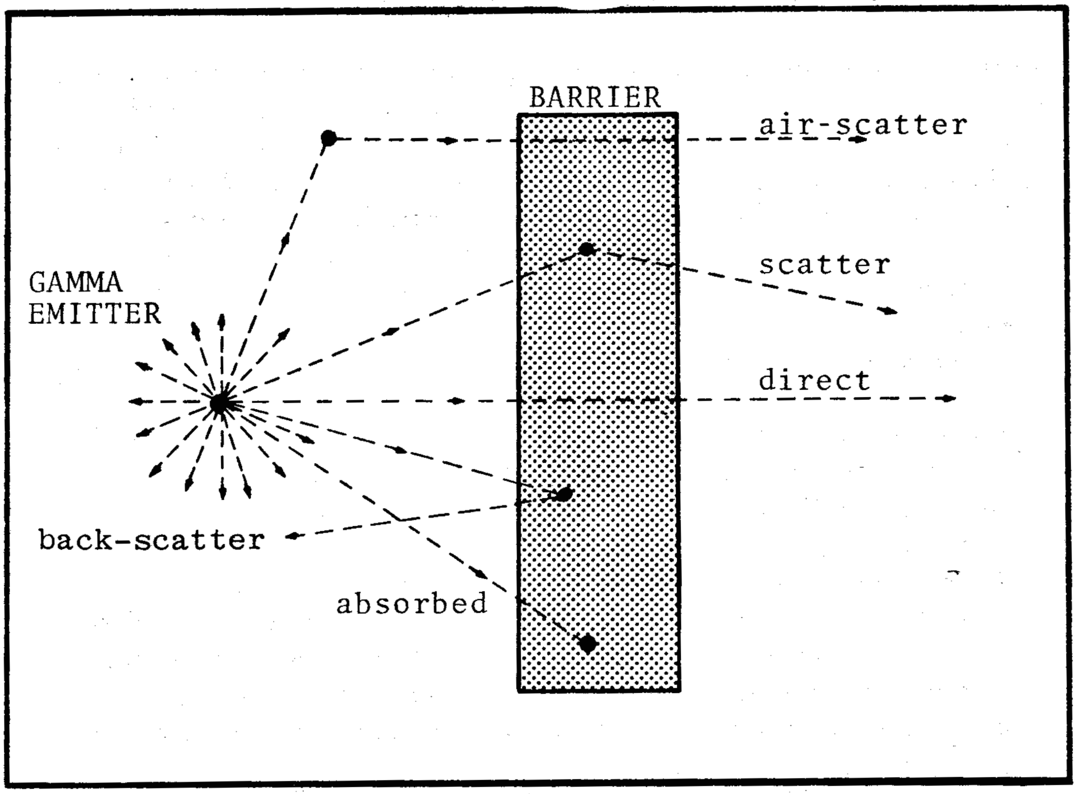

FIGURE 3-1

RADIATION EMERGENT FROM A BARRIER

3-3 Barrier Effectiveness vs. Photon Energy

Photons having high energy have a higher probability of penetrating a barrier than those having lesser energy. Therefore, a given barrier will be more effective against radiation of low energy than it will be against that of higher energy.

It has been pointed out that there are many different ways in which the nucleus of fissioned material may be split. Consequently many different fission fragments are possible, most of which are radioactive and undergo decay as a function of time. On the average, two to three decays are required in order for a radioactive fragment to reach a stable state. At any one time, something over two hundred different radioactive products may exist in the fission products from a nuclear explosion. These have half-lives ranging from fractions of a second to millions of years, and emit gamma radiation with energies primarily in the 0.2 to 3.0 million electron volts (MeV) range.

Figure 3-2 shows the distribution of gamma radiation energy from the fission products of a nuclear explosion for several different times after fission. The height of each bar is proportional to the fraction of energy content of gamma rays in the energy interval. It is noted that at about one hour after fissioning the gamma rays have energies ranging between 0.5 and 2.5 MeV. After about a day, most of the energy comes from photons with energies below about 1.0 MeV. After about 10 days the higher energies become dominant. Note that the sum of the ordinates for each case adds to unity, so that the ordinates merely indicate the fraction of the total energy. The actual total energy will be decaying with time.

Since the effectiveness of a barrier depends on the gamma energy level, it is expedient to choose a single spectrum to serve as a basis for all spectra dependent data used in the development of a method for analysis. Primary data used in the development of the "Standard Method" were derived from consideration of the spectrum that exists 1.12 hours after fissioning. This choice resulted from consideration that; this spectrum is fairly representative of other early times in terms of penetrating power, and that the greatest part of exposure to the radiation from nuclear fallout is apt to occur during the first few hours. The assumption of the 1.12 hour spectrum is on the conservative side and is not sufficiently great to warrant complications in the procedure through admission of data based on a time dependent energy distribution.

3-4 Mass Thickness

In addition to its dependence on photon energy, barrier effectiveness depends, among other things, on the type of barrier material (chemical composition) and the total mass involved. As indicated previously, barrier effectiveness depends on interactions between photons and orbital electrons. Because nearly all important construction materials have relatively low atomic numbers, attenuation in those materials is due primarily to scattering interactions which are independent of the energy state occupied by the electrons in the barrier material. Attenuation produced by a barrier is, thus, almost completely dependent on how many electrons are put in the path of the gamma rays. This is simply the product of the number of electrons per unit volume and the thickness of the barrier.

Recalling the ${}^{A}_{Z}(\ )$ notation for atomic structure (Appendix A), Z is the number of protons in the nucleus. In a neutral atom there is one electron for each proton, thus Z is also the number of electrons. In this notation A is the number of protons plus neutrons in the nucleus and since almost all of the mass

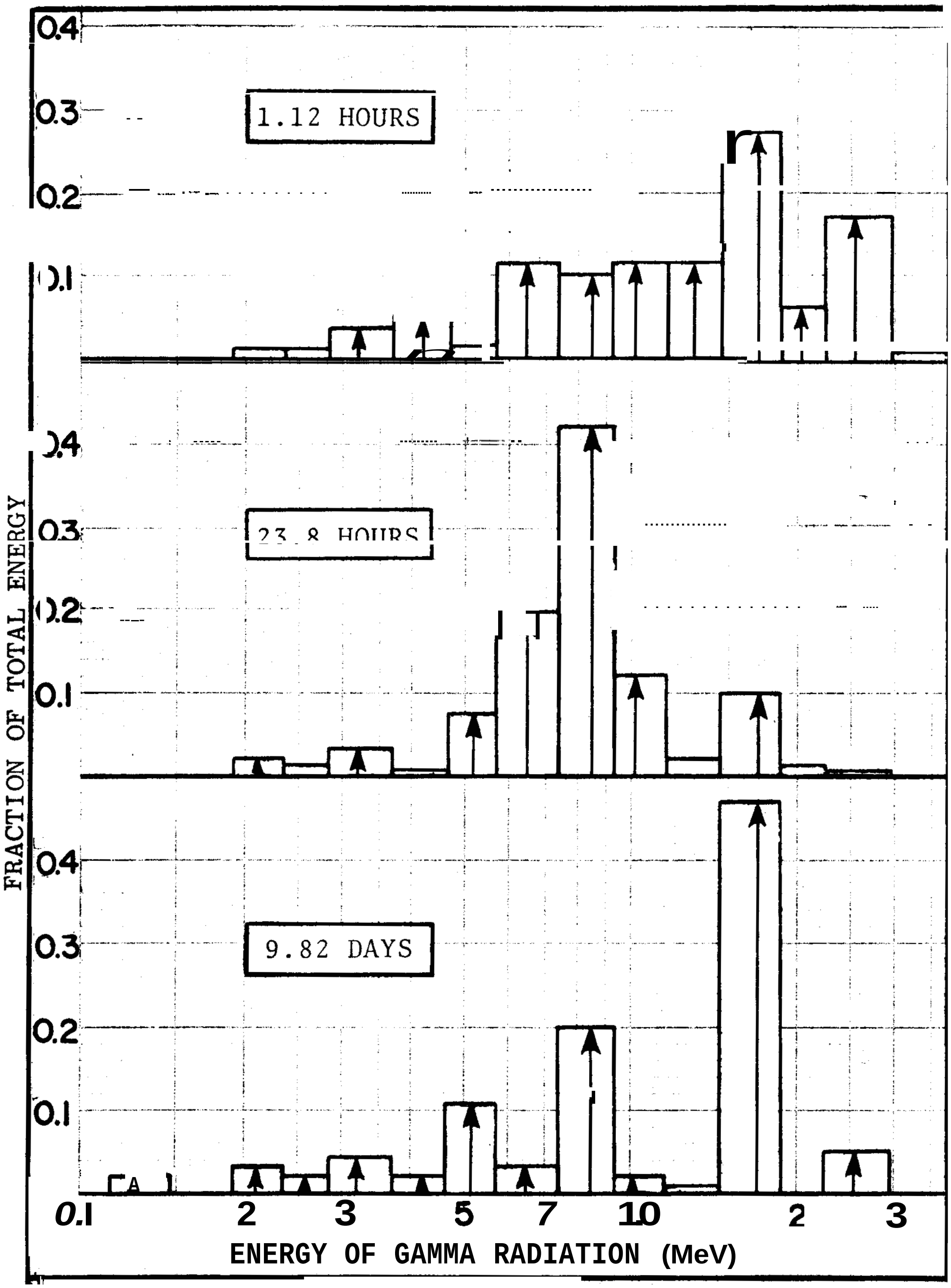

FIGURE 3-2

GAMMA ENERGY SPECTRUM AT DIFFERENT TIMES AFTER FISSION

(weight) of an atom is due to its protons and neutrons, A is closely related to the mass of the atom. The ratio Z/A is thus a measure of the number of electrons per unit weight. The number of electrons per unit volume is obtained by multiplying Z/A by the weight density (weight per unit volume) of the barrier.

The symbol X is defined as a parameter by which the effectiveness of a barrier can be measured. X is proportional to barrier thickness, t, barrier density, ρ, and the ratio of atomic charge to atomic mass, **Z/A,** all averaged over the constituent elements of the barriers.

$$X \propto (Z/A)\rho t.$$

But since Z/A is nearly 0.5 for practically all important construction materials, the parameter X is simply the product of density times thickness or, for all practical purposes in structure shielding, simply the weight per unit of area of barrier. This is termed <u>mass thickness</u>.

To determine the mass thickness of a barrier, one has merely to determine its weight per unit of area, generally pounds per square foot (psf). If the barrier is composed of more than one material, its mass thickness is the sum of the weights per unit of area of all constituents of the barrier.

<u>Examples:</u>

a. What is the mass thickness of an 8-inch thick (standard weight) concrete slab? The density of standard weight concrete can be taken as 150 lbs/ft^3.

MASS THICKNESS: $X = \frac{8}{12}\ 150 = 100\ lbs/ft^2$ (psf)

b. What is the mass thickness **of** 18 inches of soil which has a density of 100 lbs/ft^3?

MASS THICKNESS: $X = \frac{18}{12}\ \mathbf{100} = 150$ psf

A table of mass thicknesses of common construction materials is given in Appendix B.

3-5 The Standard

The protection furnished by a building is evaluated by comparing the amount of radiation received at some location within the building to that which would have been received in a completely unprotected location. To give meaning to such comparisons, it is desirable to assume some reference standard location against which protection furnished at other locations is compared. This is analogous to the situation that exists in differential leveling where the elevations of all points are referred to mean sea level.

The standard unprotected reference position used by Spencer in generation of primary data is a detector located three feet above a smooth plane infinite in extent. Fallout particles having the average energy of the mixed fission product at 1.12 hours after weapon detonation are uniformly distributed on this plane. The plane (and detector) are embedded in an infinite homogeneous medium consisting of dry air at 76 cm Hg pressure and 20 degrees centigrade temperature (standard laboratory air). In essence, the reference configuration is an infinite plane source in an infinite homogeneous medium.

Several reasons prompted this choice of the standard. The location of the detector 3 feet above the plane considers an average point at about mid-body height and/or a radiation detecting instrument carried at about that height in monitoring operations. Also for the reference conditions, the standard reference dose rate can be calculated accurately to within 2 or 3 percent.

Figure 3-3 depicts the standard unprotected location. The detector responds to photons arriving from any and all spherical directions. The photons received at the detector come directly from point sources on the plan (direct radiation) or as air-scattered radiation from points in the air.

It should be noted that, from below its plane, the detector is exposed to both direct and air-scattered radiation. From above its plane, it is exposed only to air-scattered radiation. Air-scattered radiation arriving at the detector from above its plane is termed skyshine radiation. An analogy can be drawn between it and the glare that exists over a lighted city at night. As will be seen later, of the total amount of radiation reaching the standard detector from below its plane, the direct component is overwhelmingly dominant. It thus becomes convenient to discuss the radiation from below simply as direct radiation and that from above as skyshine radiation. In this context it should always he recalled that direct radiation includes an air-scattered component.

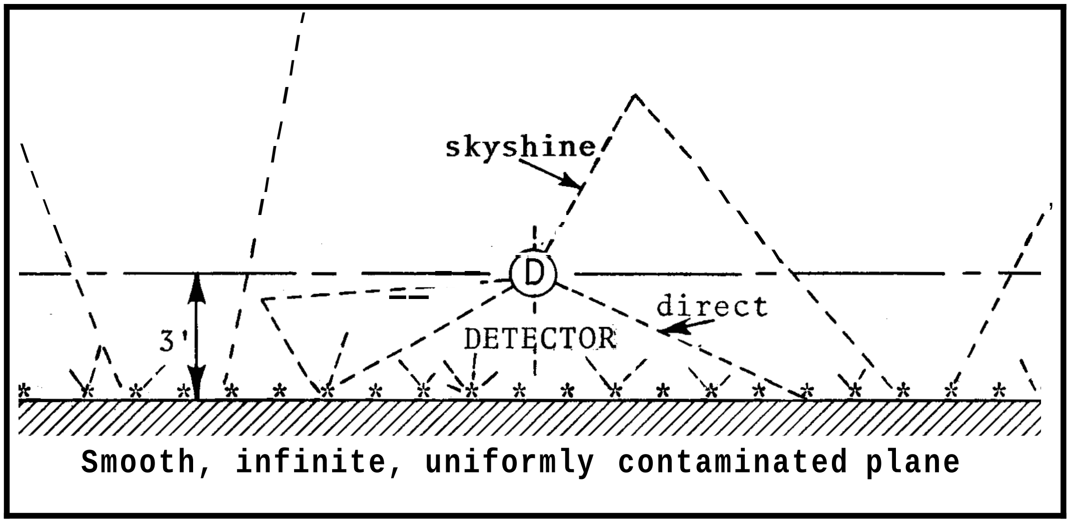

FIGURE 3-3
STANDARD UNPROTECTED **LOCATION**

3-6 Standard Detector Response Evaluated Qualitatively

Figure 3-4 considers a collimated detector located at the standard unprotected location, and pivoted so that it may be revolved in a vertical plane about its horizontal axis. When this collimated detector is pointed in a particular direction defined by the angle Θ (theta), measured from the vertical axis, it will respond to the gamma photons that approach and reach the detector from that direction. It should be obvious that, since the standard radiation field has azimuthal symmetry, it is immaterial in which azimuthal direction the detector points, the important angular quantity is the polar angle Θ . If the incremental exposure dose rate is determined for a given value of Θ covering a small increment of azimuthal angle, the total exposure dose rate for that polar angle is obtainable simply through a multiplication of the incremental exposure dose rate by the sum (integral) of all increments of azimuthal angle in the 360 degrees of azimuth about the vertical axis. The qualitiative dose rate angular distribution, i.e., the detector response as it points in different directions, is plotted in Figure 3-4.

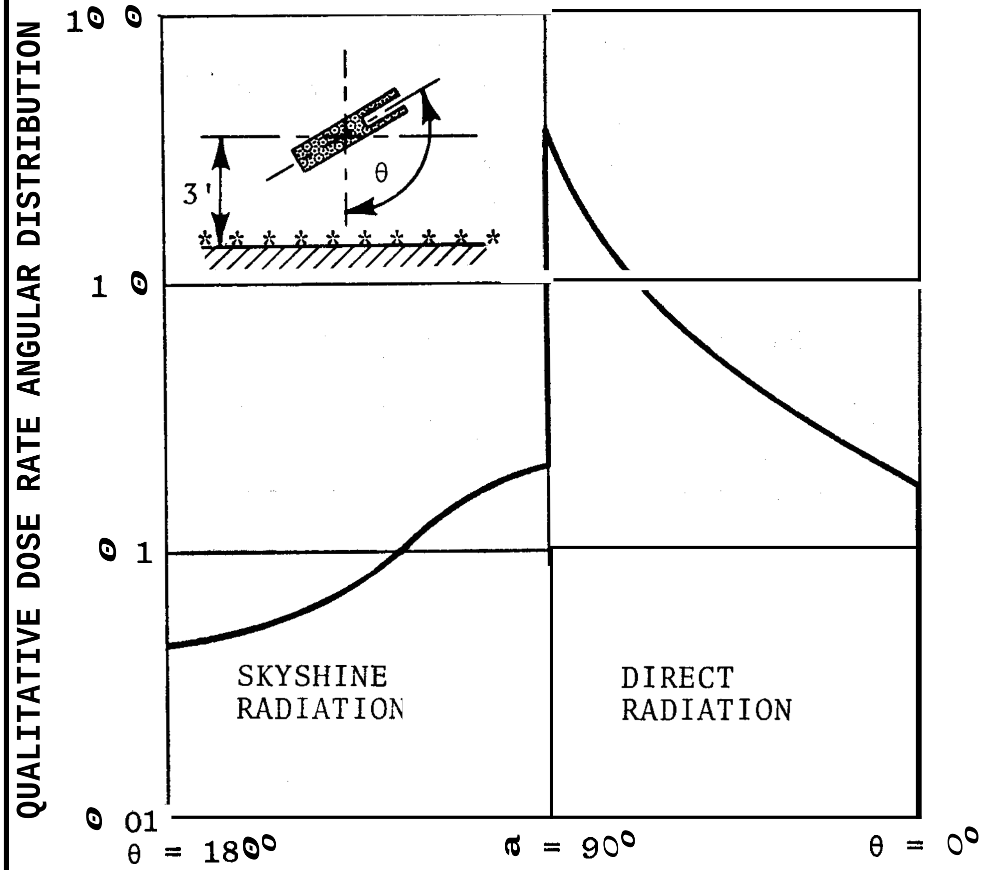

FIGURE 3-4

QUALITATIVE DOSE RATE ANGULAR DISTRIBUTION
(UNPROTECTED DETECTOR)

Figure 3-5 serves as a simplified basis for certain characteristics of the curve that are of fundamental interest. In the figure, the field of view of the source plane is a minimum number of sources, as the detector is pointed straight down. As it is rotated from the downward position ($\theta = 0°$), to values of θ up to $90°$, the field of view at the detector, projected onto the source plane, becomes increasingly greater. Obviously, these increases are proportional to the secant θ. For these increasing angles of rotation, there is indicated a possibility of response to at least direct radiation from an increasing number of sources. For θ just below $90°$, the field of view would occupy an infinite area on the source plane. In the absence of some blunting effect, it might be assumed that the response in this limiting direction just below the horizon would be infinite. This would indeed be the case were the surrounding medium a complete void. Since the medium is air, a lessening of response will occur as photons started in the direction of the detector are either absorbed or diverted through scattering interactions. The response thus peaks at some finite value when $\theta = 90°$ as indicated in Figure 3-4. Radiation reaching the detector from

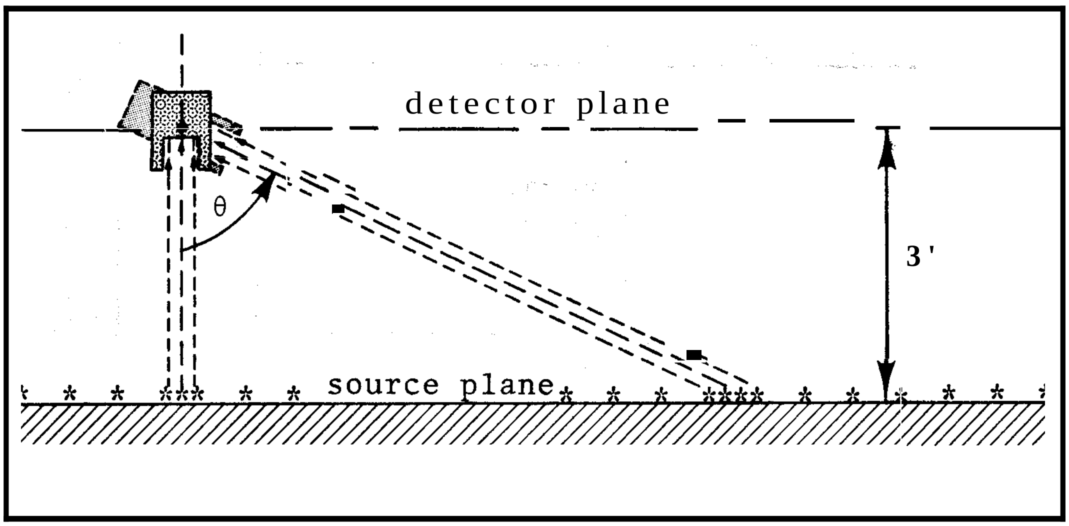

FIGURE 3-5

COLLIMATED DETECTOR - SECANT EFFECT

below the horizon (θ between 0° and 90°) is labeled "Direct Radiation- in Figure 3-4 (although this includes an insignificant air scatter component).

When the detector is pointed above the horizon, it will respond solely to air-scattered photons. Air-scattered radiation which reaches the detector from above its plane is referred to as skyshine and the left-hand portion of the qualitiative plot in Figure 3-4 is so designated. The shape of the curve in Figure 3-4 is based on the standard height of 3 feet. Different shapes would be obtained for higher detector locations.

The curve represents detector response to radiation from particular polar directions. The sum of such responses over all polar angles represents the total amount of radiation received at the standard unprotected location. Thus the area under the curve gives the total dose (or dose rate) received at the standard unprotected location. The area to the right of $\theta = 90^{\circ}$ would be the response from direct radiation from below the detector plane, and the area to the left would yield the response to skyshine from above. Recognizing that the ordinates of the qualitiative response are logarithmic, it is seen that direct radiation represents about 90% of the total dose, and skyshine represents the remaining 10%.

3-7 Protected Detector Response Evaluated Qualitatively

Figure 3-6 shows a collimated detector mounted at the standard 3-foot height in a building. The protection afforded by the building is the essential difference between Figures 3-6 and 3-4.

The building is assumed to be cylindrical and is azimuthally symmetrical. It consists of a roof and walls of some mass. The wall contains a continuous aperture. The detector of Figure 3-6 as in Figure 3-4 is rotated through successive increments of polar angle θ, and values of dose rate angular distribution are plotted against values of θ. In the qualitative plot, detector responses are superimposed on those that would accrue to the standard detector of Figure 3-4. The dashed curve segments are a reproduction of corresponding parts of the plot in Figure 3-4. The solid curve segments represent qualitative responses at the protected detector.

As the detector is pointed vertically down, it responds to no radiation since the area within the structure is clear of fallout particles, Sources which normally would have occupied this area now occupy the equivalent area of the roof. Air-scattering within the structure is assumed to be negligible.

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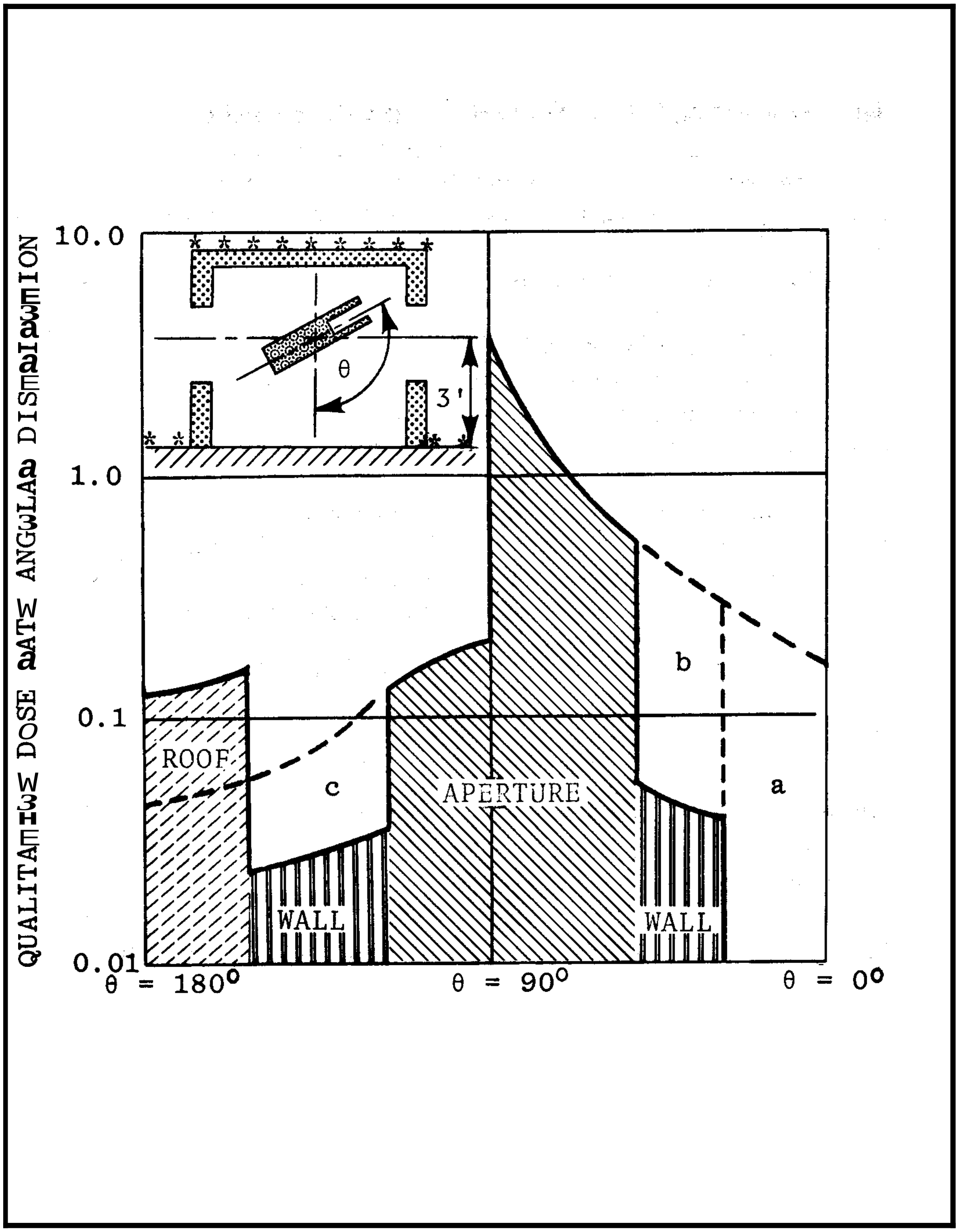


FIGURE 3-6

QUALITATIVE DOSE RATE ANGULAR DISTRIBUTION
(PROTECTED DETECTOR)

No radiation will be detected until θ is such that the collimated line of the detector intercepts the first source on the plane immediately outside the wall. The area marked "a" in the figure represents the lack of response due to the cleared area within the structure.

When the first source outside the wall is intercepted, the detector will respond. In the absence of mass in the wall, the response at this point would be exactly the same as the unprotected case. However due to attenuation in the wall the response will be less and will remain less through all angles of rotation up to that point where the line of sight of the detector intercepts the aperture. The area marked "b" in the figure represents the loss in response (compared to the standard) as the result of the effectiveness of the wall barrier. The vertically shaded area below indicates the response that has not been lost by virtue of the barrier. It includes direct radiation and radiation that has been scattered from points in the wall.

As the aperture is first intercepted in the process of rotation, the detector will respond in exactly the same as the unprotected detector while the detector is pointing through the window.

Through that next increment of rotation involving the limits of the upper wall segment, the qualitative response of the detector will be as discussed above for the lower wall portion. The area marked "c" represents the loss resulting from the effectiveness of the wall as a barrier. This response is due to skyshine and wall-scatter radiation.

As the detector is rotated further, its line of sight will intercept the roof surface and it will respond to radiation of several origins. These include; direct radiation from sources on the roof, skyshine from above, scatter radiation from points within the roof barrier, and ceiling shine. Ceiling shine consists simply of backscatter radiation from the ceiling to the detector as the result of direct radiation from ground sources passing through the aperture and impinging on the ceiling. In the case of the unprotected detector, the response was only to skyshine. The response in the protected case for angles of rotation intercepting the roof can be greater or lesser than the unprotected response. This depends on how effective the roof barrier is in attenuating the radiation. In the plot it has been assumed that the response is greater. It is significant to note that the loss represented by area "a" in the figure has now been at least partially recovered.

The qualitative plot of Figure 3-6 helps to explain the meaning of the "Protection Factor," PF. If the plot were to a linear scale, the area under the curve for the protected detector would give a relative indication of the total radiation received. The ratio of this area to the area under the curve

for the standard unprotected location yields a decimal fraction termed a "Reduction Factor," RF. It indicates how effective various features of the shelter are in reducing radiation reaching the protected detector as compared to the standard. A reduction factor of 0.01 would indicate, for example, that the protected location receives only 1% of the radiation that would be received at the standard unprotected location A.

The 'Protection Factor," PF is simply the reciprocal of the reduction factor. A PF of 100, corresponding to an RF of 0.01, indicates a protected location **100** times better than the standard unprotected location in terms of exposure.

3-8 Protection Factor

It has been shown that a protection factor indicates the degree of protection furnished by a building at a specific point location within as compared to the standard unprotected location. In article 3-5 the standard detector and its location were defined. It is significant that the standard as defined does not consider the intensity of radiationassociated with the uniformly contaminated field. Therefore the protection factor does not give a direct indication of the fallout radiation hazard. Such hazard is a function of the degree of contamination as well as the protection factor. It follows that a protection factor provides merely a means for comparison of structure against structure. An estimate can be made of the degree of contamination that might be expected in a given area, a design protection factor can be selected that will give reasonable assurance that a certain biological hazard will not occur.

3-9 The Essence of Shelter Analysis

Referring to Figure 3-6, the total area under the shaded curve can be considered as a reduction factor expressed as a decimal fraction. The total area under the response curve in the figure has been divided into several sub-areas. These sub-areas represent portions of the reduction factor corresponding to contributions to the detector of radiation emerging through the solid parts of the walls, through the apertures, and through the roof. In the application of the standard method, one makes separate calculations for contributions through walls, apertures and roofs. The sum of these contributions yields the total reduction factor, the reciprocal of which is the protection factor.

In Figure 3-6 the difference between the protected response and the unprotected response for any of the sub-areas is due to barrier effects and geometry effects. The height to the curve is almost purely a function of the effectiveness of the barrier in attenuating the radiation. The greater this effect, the lower the response values. The width of any sub-area is purely a function of the total angle of rotation involved and is consequently a geometry effect controlled by the physical dimensions of the structure. Thus, a contribution (C) may be considered as the product of a barrier factor (B) and a geometry factor (G). In application of the standard method for finding contributions, one is required to calculate certain geometric quantities from the physical dimensions of the building and to determine the mass thickness of the various barriers. With the aid of curves and charts, barrier effects and geometry effects are evaluated, all contributions are calculated, and the protection factor is determined.

3-10 Solid Angle Fraction

The effect of building geometry on detector response can be evaluated by considering the volume inside the building through which the radiation must pass in order to arrive at the detector. Figure 3-7 considers a contaminated plane above a centrally located detector. Rays drawn from the edges of the contaminated plane to the centrally located detector below, form an inverted pyramid with the detector at its apex and the contaminated plane its base. All radiation which reaches the detector from this contaminated plane does so on straight lines lying wholly within this pyramid volume. Three dimensions, W, L and Z, shown on the figure, have an effect on this volume and, consequently, determine the effect of geometry on detector response.

A solid angle Ω, shown at the apex of the pyramid, is used as a single parameter to characterize the effect of building geometry. A change in any of the three dimensions, W, L or Z, will produce a change in Ω. As W or L or both increase or decrease (Z remuining constant)& increases or decreases. As Z changes (Wand L remaining constant), Ω will charge, increasing with decreasing values of Z and decreasing with increasing values. Thus, Ω, dependent on all three dimensions, is a single geometric parameter that can be used to relate detector response to physical dimensions.

Just as plane angles are measured in radians, solid angles are measured in "steradians." In plane geometry, radian measure is related to the length of arc which an angle intercepts on a circle of unit radius Analcgous to this, a solid angle is measured in terms of the surface area it subtends on a sphere of unit radius.

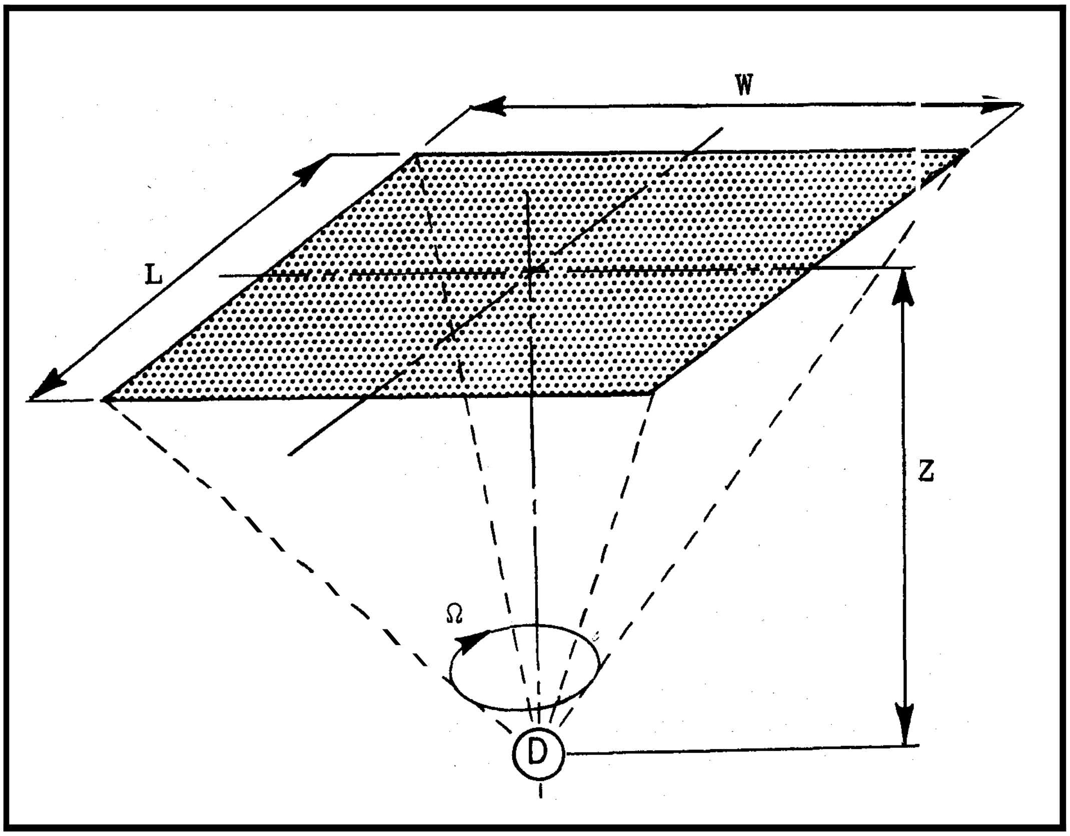


FIGURE 3-7

SOLID ANGLE SUBTENDING RADIATION SOURCE

Figure 3-8 shows, in (a), a detector subtending a circular area and, in (b), a detector subtending a rectangular area. The solid angle at the detector is the area, A, subtended on the surface of a sphere of unit radius. In fallout shelter analysis it is more convenient to work with "solid angle fractions" than solid angles. The solid angle fraction ω (omega) is defined as the area A (which the solid angle subtends on a sphere of unit radius) divided by the area of a hemisphere of unit radius.

A plane area of infinite extent would subtend an entire hemisphere and thus would have a solid angle fraction of 1.0. Solid angle fractions for plane areas obviously cannot exceed unity in value. The hemispherical concept also explains the fact that a solid angle fraction is a solid angle divided by 2π since the total solid angle at the center of a hemisphere is 2π steradians.

An expression for the solid angle fraction for a circular area is given in Figure 3-8(a). In order to develop a similar expression for rectangular areas, the area A in Figure 3-8(b) must be evaluated. The resulting expression for the solid angle fraction ω subtending a rectangular area W by L at a distance Z is:

$$\omega = \frac{2}{\pi} \tan^{-1} \frac{W/L}{2(Z/L)\sqrt{4(Z/L)^2 + (W/L)^2 + 1}}$$

In every fallout shelter analysis problem one or more solid angle fractions have to be evaluated. To avoid having to use the time-consuming equation, a chart has been developed for the determination of ω. Figure 3-9 gives ω in terms of the dimensionless ratios:

$e = W/L$ = eccentricity ratio (width to length)

$a = Z/L$ = altitude ratio (altitude to length)

where W and L are, respectively, the width and length of the base of the pyramid with ω at its apex; and Z is the altitude of the pyramid.

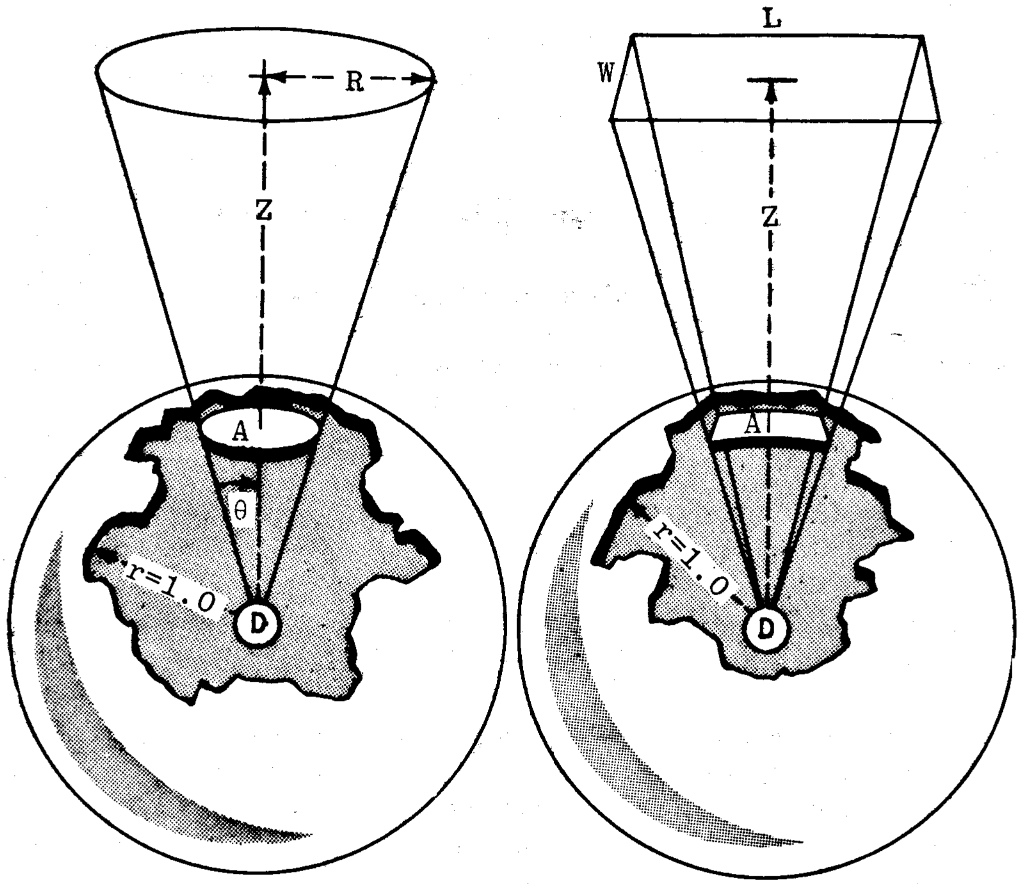
To use the chart, one normally calculates values of W/L and Z/L from known physical dimensions and determines ω from the curves. For example, if W = 50, L = 100, and Z = 20, W/L = 50/100 = 0.50 and Z/L = 20/100 = 0.20. To get ω one draws a vertical line through W/L = 0.5, a horizontal line through Z/L = 0.2, and reads ω at the point of intersection of these lines. This example is shown in Figure 3-9 and the value of ω is estimated to be 0.51.

For convenience, Figure 3-9, together with other charts used in making fallout calculations, are reproduced in Appendix C at the end of the manual. Figure 3-9 appears as Chart 1A. Once the charts have appeared in the text and have been discussed, reference to them in subsequent calculations will be in terms of chart numbers in Appendix C.

$$w = 1 - \cos\theta$$

where $\tan\theta = \frac{R}{Z}$

$$\omega = \frac{A}{2\pi r^2}$$



(a) CIRCULAR AREA (b) RECTANGULAR AREA

FIGURE 3-8
SOLID ANGLE FRACTIONS

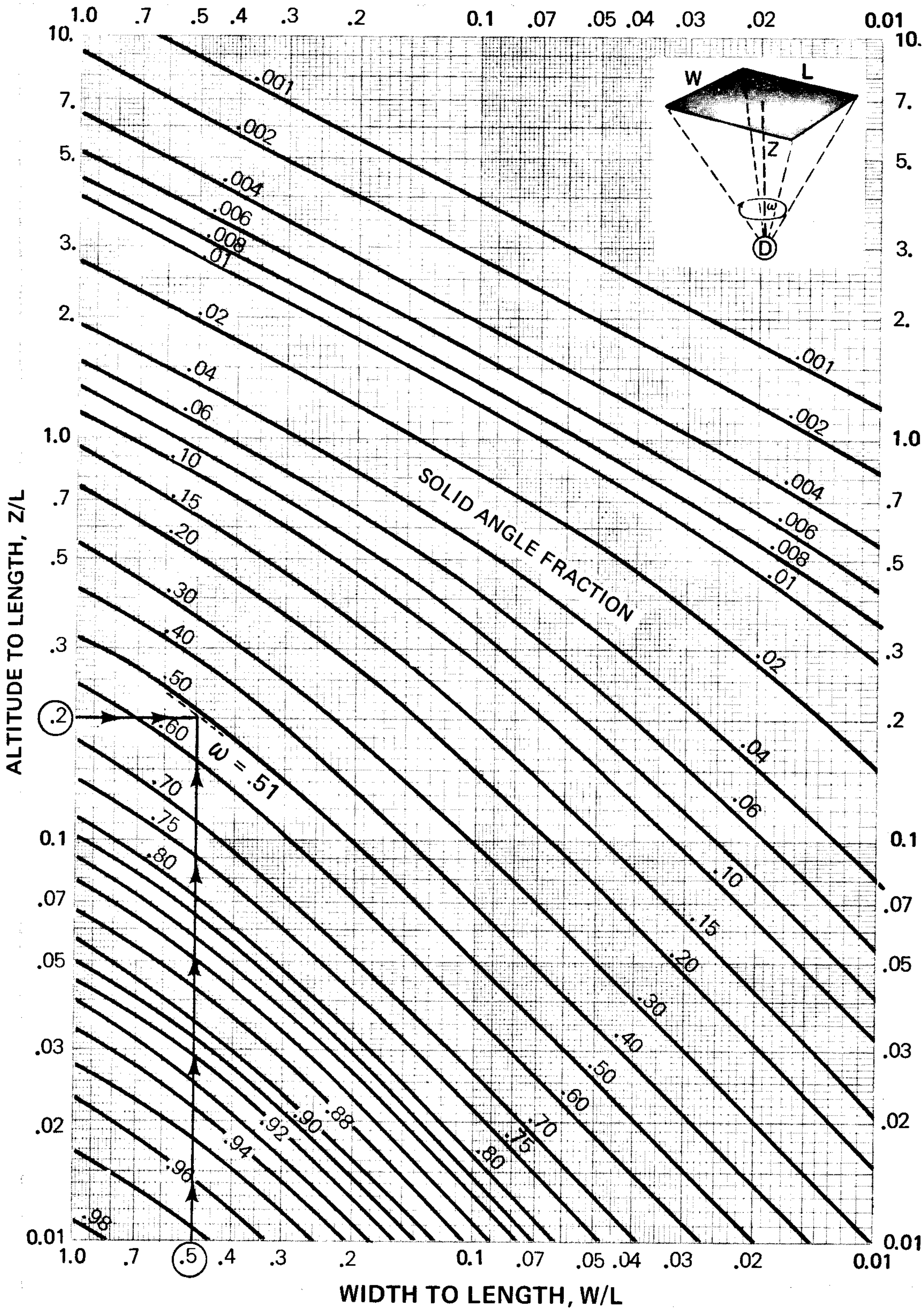


FIGURE 3-9

SOLID ANGLE FRACTION, ω(W/L,Z/L)

(CHART 1-A APPENDIX C)

Study Questions and Problems for Chapter 3

1. What type of nuclear radiation from fallout is the sole consideration in fa1lout shelters?

2. What is the purpose of fallout shelter analysis?

3. Define direct radiation, scatter radiation, and skyshine radiation.

4. Qualitatively, what is the relationship between barrier effectiveness and photon energy?

5. Why is it necessary, in the development of the analysis method, to choose a single spectrum for gamma radiation energy distribution, and what spectrum has been chosen?

6. Define mass thickness, its units, and comment on the relative effectiveness as barrier material of common construction materials.

7. Describe the standard unprotected (detector) location and explain the purpose of this standard in fallout shelter analysis.

8. To what kinds of radiation is the standard detector subjected, and what is the source of each kind?

9. Sketch, the standard detector response to radiation from all directions.

10. By means of a sketch, show how the angular distribution curve for a protected location differs from that for the same detector unprotected.

11. Define; contribution, reduction factor, barrier factor, and geometry factor and protection factor.

12. What is the significance of a protection factor of 100?

13. Explain why a protection factor, in itself, does not give a direct indication of the fallout radiation, biological hazard.

CHAPTER IV

FALLOUT SHELTER ANALYSIS OF SIMPLE BUILDINGS

4-1 Introduction

In this chapter, the DCPA Standard Method for Fallout Gamma Radiation Shielding Analysis will be developed and applied to a wide variety of simple buildings.

The discussion of Chapter III was presented to enable a fallout shelter analyst to make a qualitative evaluation of the effect of variations in pertinent parameters on the protection provided by a structure. The ability to make such qualitative evaluations is one of the most valuable tools in the mental equipment of a shelter analyst or designer. Its importance cannot be overemphasized.

The approach to be used in the development of the Standard Method will be to begin with a simple one-story "blockhouse," devoid of complicating features. Progressively more and more real building parameters will be added such as: interior partitions, basements, windows, mulfi-stories, irregular shape, and adjacent buildings, until all basic considerations in fallout shelter analysis have been developed. Complex shielding applications and design techniques will be presented in the next chapter.

The format for the development of the methodology will be to discuss each shielding parameter qualitatively before presenting the data for making quantiative calculations of contributions, reduction factors, and protection factors.

Various aspects of geometry and barrier that are significant in shielding problems are discussed from a qualitative point of view with explanations of how variations in certain parameters would probably affect the calculated protection factor.

In the development of the standard method of analysis frequent reference will be made to the work of L.V. Spencer reported in Structure Shielding Against Fallout Radiation from Nuclear Weapons, National Bureau of Standards Mongraph 42, June 1, 1962 and to that of C.M. Eisenhauer reported in An Engineering Method for Calculating Protection Afforded by Structures Against Fallout Radiation, National Bureau of Standards Monograph 76, July 2, 1964. Basic data used in the standard method were generated by Spencer. Conversion of that data to compilations and plots most convenient

for use in engineering applications was accomplished by Eisenhauer. These two documents form the foundation for the standard method of analysis.

The importance of a full understanding of this chapter cannot be over-emphasized. It will later be seen that the analysis of complex buildings involves only simple extensions of the concepts developed in this chapter. If it is clearly understood, no difficulty should later be experienced in the analysis of the most complex of buildings.

4-2 Functional Notation and Charts

In the standard method relationships are developed and expressed in mathematical form utilizing functional notation. When two variables are so related that the value of the first is determined when the value of the second is given, then the first variable is said to be a function of the length of a side, L. The second variable, L, to which values may be assigned at will (within limits depending on the problem) is called the independent variable or argument. The first variable, whose value is determined when the value of the independent variable is given, is called the dependent variable or function. Frequently, when two related variables are considered, either may be fixed as the independent variable; but, the choice once made cannot be changed without certain precautions and transformation. Again, for example, the area of a square is a function of the length of its side. Conversely, the length of the side of a square is a function of its area,

The general symbol f(x) is a functional notation. The letter f represents the dependent variable or function and x represents the independent variable. In terms of the example above, functional notation could be written as A(L) or L(A) depending on what is chosen as the independent variable. Considering **A(L),** the expression indicates that a given value for L determines the value of A. Parentheses do not indicate multiplication. They are used simply to set the independent variable.

The value of a function is often determined by more than one independent variable. For example, relative to solid angle fractions, $\omega(e,a)$ indicates that the function, ω, is determined when unique values are assigned to each of the independent variables, e and a. Stated in another way, ω cannot be determined until values of e and a are determined. Independent variables may, themselves, be functions of other independent variables; i.e., e(W, L) and a (Z, L). Thus when unique values of W, L and Z are assigned, the functions of e and a are determined. Such determined values of the functions e and a lead to the deter-

mination of the function ω. Since functional notation is extensively used in this manual, it is important for the user to recognize it when it is used and, further, to recognize the relationships that such notation indicates.

The approach to fallout shelter problems using the standard method is to first write the functional expression representing the solution. In some cases the functional expression will be quite simple, but in most cases lengthy, complex expressions will be obtained. After the functional expressions have been written, numerical values are obtained using a series of charts. One of these charts, namely Chart 1A (Solid Angle Fraction) has already been discussed. Chart **1A** merely represents the solution of a fairly simple closed form equation. Most of the other charts, however, are based on lengthy (computer) calculation for which simple closed form equations do not exist. Throughout this chapter the basis for, and the use of, each chart will be discussed. The complete set of Standard Method charts is contained in Appendix C.

4-3 Basic Structure

4-3.1 Basic Blockhouse Description

The key to full understanding of fallout shelter shielding analysis is a simple one-story blockhouse. This building is assumed to be isolated on a horizontal, plane field extending infinitely in all directions. It is rectangular or circular in plan with its floor at grade The walls are assumed to contain no apertures (openings) and are of uniform mass thickness. Radioactive fallout particles are assumed to be uniformly distributed over the entire plane surface outside the building and over the entire roof surface.

The end result of an analysis of the radiation shielding properties, of the building described above, is the determination of a protection factor. Protection factors can be calculated only for a point location. The focal point of the calculations becomes a fictitious detector located at some specific point location within the building. For the immediate purpose, it is assumed that the detector is located centrally in plan and at some height H above the floor. It responds to radiation received from all directions.

The basic building with a centrally located detector is shown in Figure **4-1.** Certain symbols are noted. Throughout this text, symbols will be defined as they first appear. A complete list of symbols is given in the front of the manual.

H = the vertical distance from a contaminated ground plane to the detector.

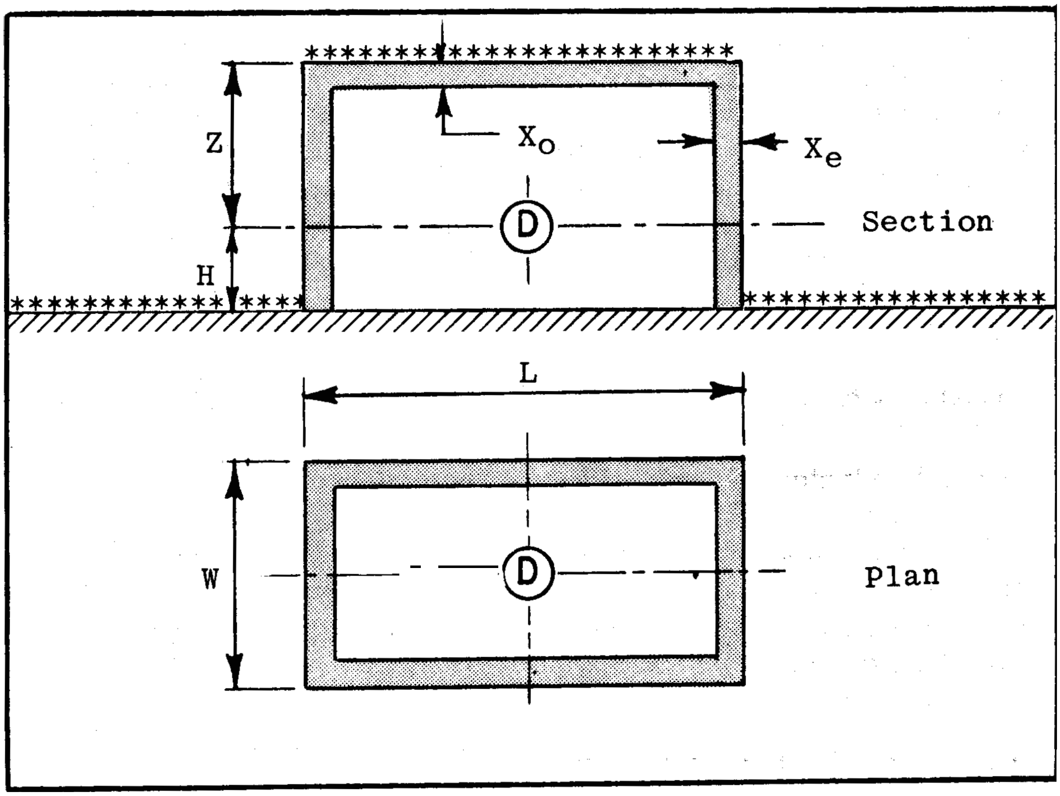


FIGURE 4-1

THE BASIC RECTANGULAR BUILDING

L = the length or greater plan dimension of a rectangular building.

W = the width or lesser plan dimension of a rectangular building.

R = the radius, in plan, of a circular building.

X_e = the mass thickness (weight in pounds per square foot of surface) of the solid portions of an exterior wall.

X_o = the mass thickness of all horizontal barriers between the detector and the contaminated roof plane or, simply, the overhead mass thickness.

Z = the vertical distance from a contaminated overhead plane to the detector.

It should be noted that the shaded wall and roof outlines are not intended to represent physical dimensions. Relative to the horizontal dimensions and story heights of a building, the actual thickness of vertical (wall) and horizontal (roof and floor) barriers are usually of second order importance and can be neglected. In the calculations, the building can be represented as a line drawing, using outside dimensions. •

4-3.2 Detector Response

The sources of radiation reaching the detector in the basic building are the radiating fallout particles on the contaminated plane below the plane of :he detector (the ground plane) and those on the contaminated plane above the plane of the detector (the roof plane). Ultimately, the detector receives radiation from the ground and from overhead.

C_g = a contribution at the detector due to radiation that has first emerged from the exterior walls of a building; referred to as a wall (or ground) contribution.

C_o = a contribution at the detector due to radiation that has first emerged from the roof of a building; referred to as roof (or overhead) contribution.

Although the detector responds to radiation that originates on the ground or on the roof, it does so only as the radiation emerges from the inner surfaces of the wall and roof barriers. From the strict point of view of the detector,

the walls and the roof are the radiating surfaces and one *may* speak inter- changeably of ground or wall contributions and of overhead or roof contributions. Figure 4-2 shows the radiation paths to the detector. This is an extension of the

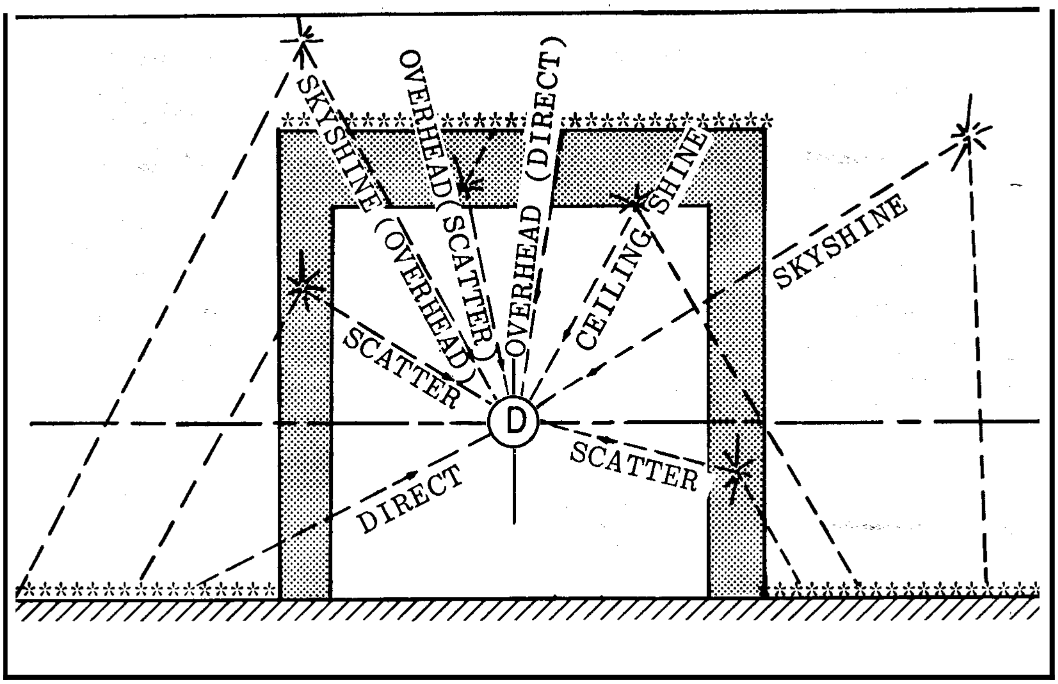


FIGURE 4-2

RADIATION PATHS TO THE DETECTOR

concepts presented in article 3-2 concerning the character of radiation emerging from the inner surface of a barrier from a single radiating particle. The effect of the planar distribution of the many particles considered here is largely one of magnitude. The character of emergent radiation is the same. It is either direct, barrier-scattered or air-scattered. **To** get the protection factor of the basic building, the overhead contribution C_o', and the ground contribution C_g must be evaluated.

4-3.3 The Overhead Contribution, Co

Attention is first focused on radiation which emerges from the underside of roof barrier in Figure 4-2, and reaches the detector as overhead contribution Co. Overhead contribution has three basic components: direct (overhead) radiation which travels in straight lines from fallout particles on the roof to the detector, scatter (overhead) radiation which as a result of scattering interactions in the roof barrier is "aimed" at the detector, and skyshine which originates from sources on the ground or on other planes such as the roofs of adjacent buildings and the roof of the subject building, and arrives at the detector after passing through the roof barrier, Ceiling shine contributions, i.e., radiation which comes through the wall and scatters in the ceiling (overhead barrier), will be handled as part of the ground contribution C_g.

In NBS Monograph 42, Dr. L.V. Spencer developed a solution for aetector response to a circular source of radiation with a barrier mass concentrated at the source. Spencer's consideration of a barrier mass concentrated at the source plane corresponds basically to the practical case of the detector in the basic one story building. In such cases, the detector is separated from the overhead plane of contamination by one intervening horizontal barrier, the roof mass itself which is concentrated at the source plane.

One major difference between the Spencer model and practical cases, is apparent from a consideration of geometry In most buildings roof geometry is rectangular while the Spencer model considers circular disc planes. Figure 4-3 is a schematic representation of actual and model configurations. In (a) the detector is located centrally below a rectangular source plane with a barrier of mass thickness, X_o, concentrated at the source plane. **A** solid angle fraction, ω, subtends the source plane, the base of a pyramid defined by rays extending from the boundary of the base to the centrally located detector point below. The Spencer model in (b) considers a detector point centrally located below a circular source plane, a mass thickness of X_o concentrated at the source plane and a solid angle fraction, ω, subtending the base of a cone.

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The circular roof model can be used to approximate overhead contributions from rectangular roofs within certain practical limits. Studies involving the fairly extreme case of a rectangular source having a length five times its width and involving a detector first very close and then very far from the source, indicate errors of at most 20% in the approximation. Most practical cases will have much smaller differences because rectangular roofs are usually less eccentric than these extremes, and angular distributions, dependent on the detector position relative to the source plane, will thus be less severe. It is important to note that errors are generally on the conservative side if the circular disc approximation of a rectangle is used.

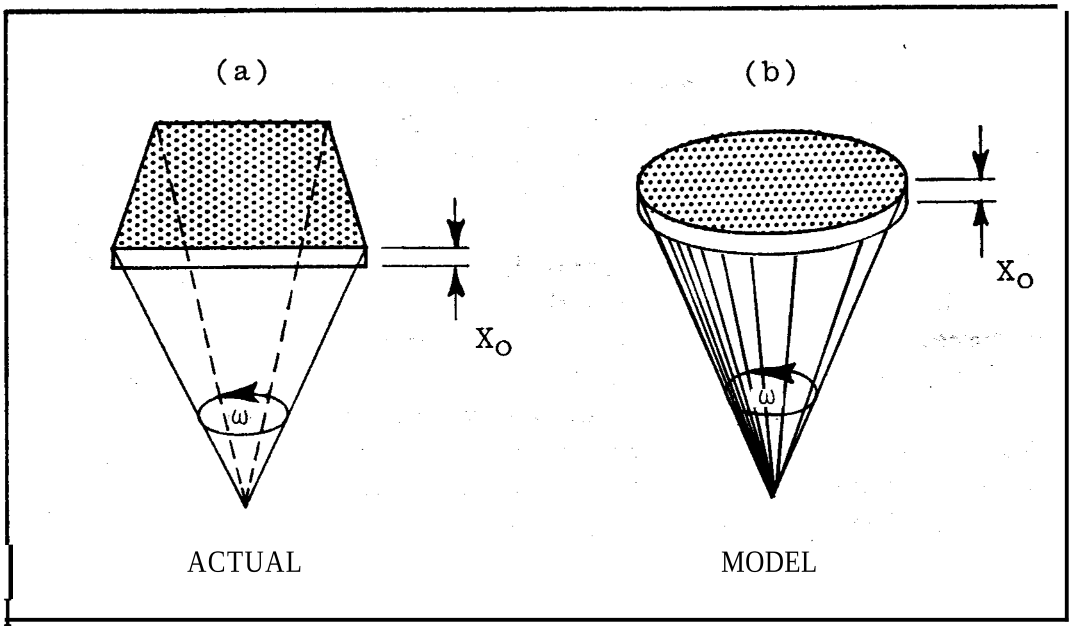


FIGURE 4-3
ACTUAL vs, MODEL OVERHEAD CONTRIBUTION

A second major difference between Spencer's model as shown in Figure 4-3 and practical cases arises out of the fact that, in an actual situation, several discrete horizontal barriers may lie between the source plane and the detector position. Such is the case if the detector is located in other than the uppermost story of a multi-story building. Such cases could be approximated by another of Spencer's models which considered a detector separated from the source plane by a homogeneous mass uniformly distributed between the source plane and the detector. In fact, earlier versions of the standard method of analysis utilized Spencer's data for this model in solutions for such cases. However, experimental studies have revealed better (but still conservative) agreement with predictions from the model of Figure 4-3 even when several separate barriers are present between the source plane and the detector. In the present version of the standard method, the model of Figure 4-3, serves as the basis for determining overhead contributions for all cases.

Summarizing the standard method utilizes data derived by Spencer for the model shown in Figure 4-3 in calculating overhead contributions. These data are plotted in Figure 4-4 (Chart 9 in Appendix C.) If the detector is separated from the overhead source plane by more than one horizontal barrier, the total intervening mass is considered concentrated at the source plane. X_o becomes the sum of the separate mass thicknesses of all the intervening horizontal barriers. Although usual cases involve rectangular source geometry, the standard method assumes that data for circular source geometry are applicable, if the solid angle fraction, ω, subtending the rectangular plane is equal to that subtending the circular plane.

4-3.3 Calculation of Overhead Contribution, Co

Figure 4-4 (Chart 9, Appendix C) shows that the overhead Contribution **Co** depends on two basic parameters. Geometry effects are accounted for by the solid angle fraction, ω, and barrier effects are accounted for by the overhead mass thickness Xo. In functional notation this is written $Co(Xo, \omega)$. In order to get Co from Figure 4-4, both Xo and ω are needed. As an example of the use of Figure 4-4 consider the case in which Xo = 150 psf and ω = 0.40. Enter Figure 4-4 with 0.4 on the ω scale and proceed vertically until the curve representing a mass thickness of 150 psf is reached, and then proceed horizontally to the scale on the left to read Co = .0035. In real life problems and Xo are not given and must be calculated from the building properties. Problem 4-1 shows the calculations for getting overhead contribution Co from basic building properties.

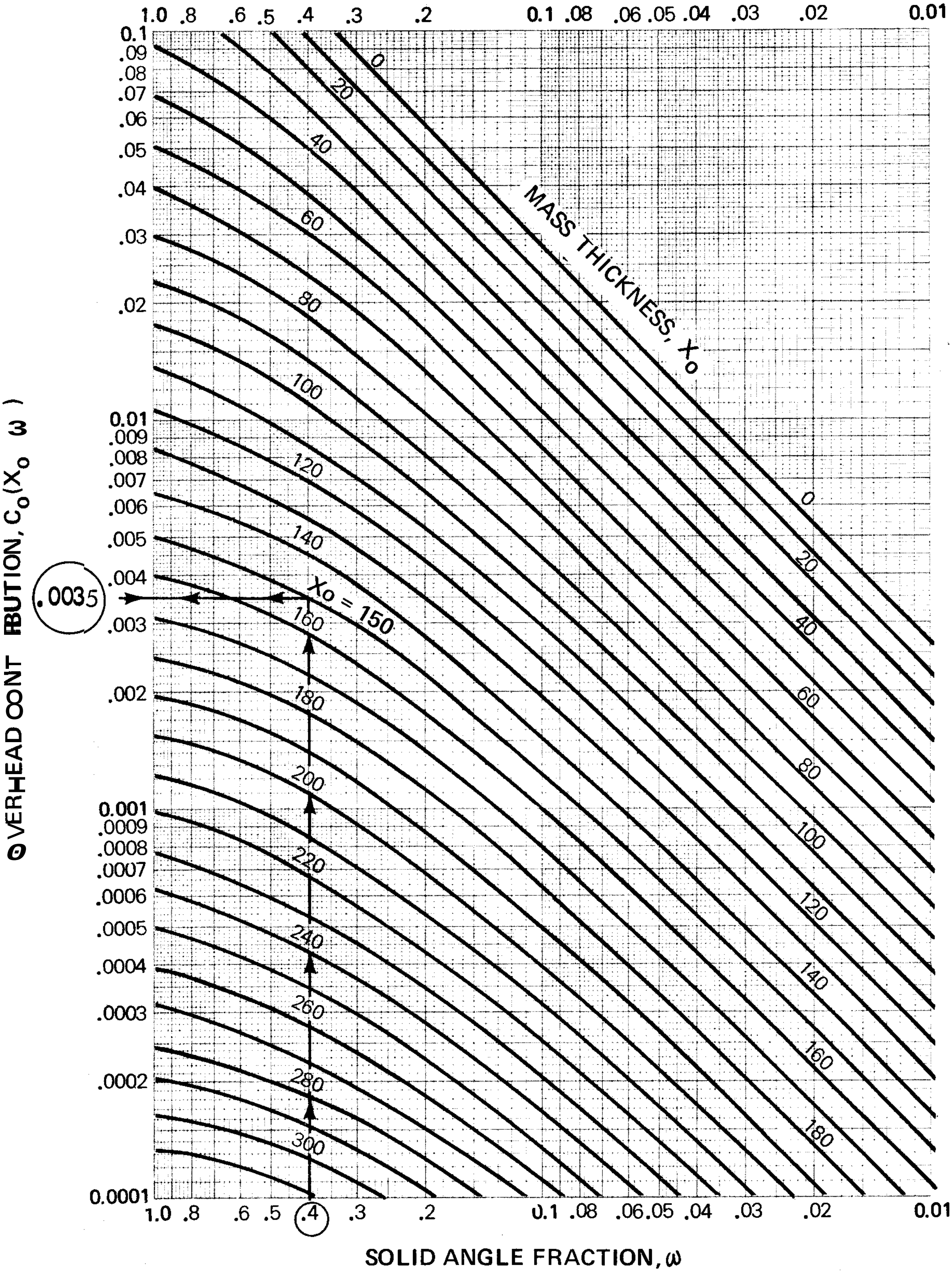


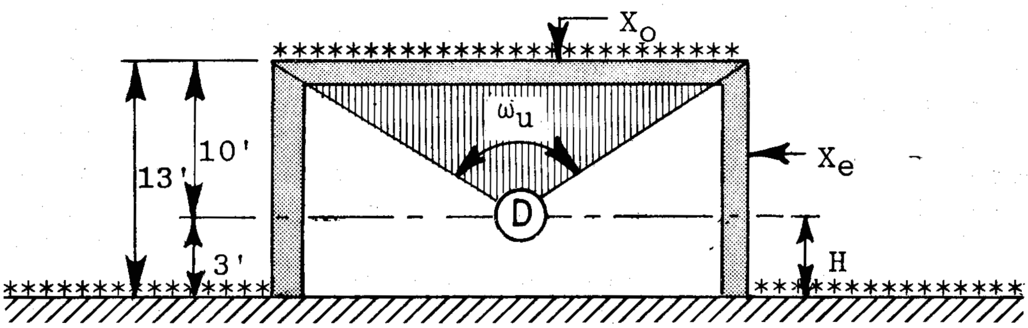
FIGURE 4 - 4

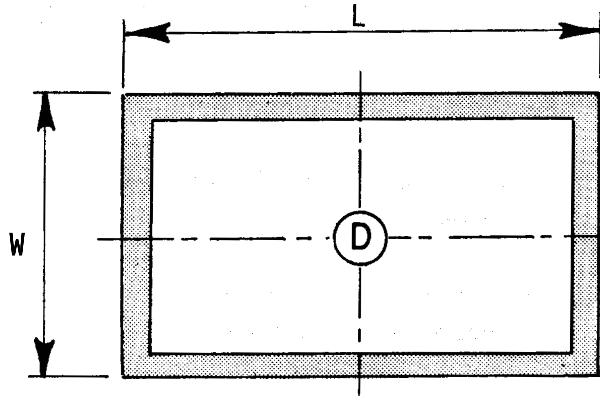
OVERHEAD CONTRIBUTION, $Co(X_o\ ,\omega)$

(CHART 9-APPENDIX C)

PROBLEM 4-1

Consider a simple, one-story, aboveground building having a width, W, of 40 feet and a length, L, of **60** feet, **A** centrally located detector lies at a distance, H, of **3** feet above the contaminated fround plane and at a distance, Z, of 10 feet from the contaminated roof plane. The roof construction is a one foot thick standard weight concrete slab It is assumed that the building is isolated in a contaminated field of infinite extent and that radioactive particles are uniformly distributed on the roof. Find the overhead contribution C_o.





W = **40'**
L = **60'**
Z = **10'**
X_o = **12"** thick concrete slab

a) Find the solid angle fraction, $\omega_u(W/L, Z/L)$

$\frac{W}{L} = \frac{40}{60} = 0.67 \qquad \frac{Z}{L} = \frac{10}{60} = 0.167$

$\omega_u(W/L, Z/L) = \omega_u(0.67, 0.167) = \mathbf{0.64}$ (Chart 1A)

b) Find the overhead mass thickness, X_o

Standard weight concrete has a weigh- density of 150 lbs per cubic foot. Therefore a one-foot thick slab would have a mass thickness of 150 psf.

c) Overhead contribution:

$C_o(\omega_u, X_o) = C_o(0.64, 150) = 0,0043$ (Chart 9)

A detector located beneath a contaminated roof plane will respond not only to radiation originating with the fallout particles on the roof but also to a certain amount of skyshine. As explained earlier, skyshine is radiation resulting from scattering interactions of photons in the air and passes directly through the barrier to the detector without further interaction. Chart *9* (Figure 4-4) includes the effect of skyshine through the solid angle fraction subtending the roof and no additional consideration need be given for the usual cases. For the special case, involvinga roof that may have been cleared of contamination by some effective means, the only contribution through the roof would be skyshine. This matter is considered as a special case later.

A further study of Figure 4-4 (Chart *9)* reveals that it is not necessary to compute ω to a fine degree of precision. Generally, two places after the decimal point, are sufficient. It may be further observed, from a study of the figure, that, particularly for relatively high mass thicknesses, overhead contributions are relatively insensitive to changes in values of the solid angle fraction in the range 0.6 to 1.0. This indicates that beyond a certain limit, increases in area will have very little effect on overhead contribution. Stated in another way, the major portion of the overhead contribution stems from sources in the centrally located region of the area. There is no reason to be extremely precise in establishing the dimensions **W** and **L,** particularly if they are large.

4-3.5 The Ground Contribution Cg

Consider in Figure 4-2 the radiation emerging from the inner surface of the exterior wall barriers. The centrally located detector responds to this radiation as it arrives from all angular directions. All of the radiation reaching the detector through the walls originates from the fallout particles on the contaminated ground plane and the aggregate is the ground contribution, Cg. As indicated in Figure 4-2, it comes either directly from the source through the wall without an interaction, or *as* radiation that has scattered in the wall or ceiling barrier, or *as* radiation that has undergone a scattering interaction in the air and then passes directly to the detector through the wall barrier without further interaction.

Several very important shielding considerations become apparent through a study of Figure 4-2.

1. Since direct radiation travels in a straight line from sources on the contaminated plane, through the wall, to the detector, direct radiation can come through only that portion of the wall below the plane of the detector.

2. Each photon incident upon the wall may enter into a scattering interaction within the wall barrier; and, hence, every point on the interior of the wall is a potential contributor of scatter radiation to the detector. Scatter radiation may thus reach the detector from those portions of the wall both above and below the plane of the detector.

3. A scattering interaction may take place at any point in the air above the contaminated ground plane and departing air-scattered radiation may pass directly to the detector through either the portion of the wall above or below the detector. As explained in Chapter III, air-scatter which arrives at the detector from above its plane is called skyshine. Air-scatter which arrives from below the detector plane is included as a component of what is termed direct radiation. Any air-scatter which undergoes a further scattering in a barrier and then is intercepted by the detector can be considered as a component of the wall-scattered radiation referred to simply as scatter.

4. Although Figure 4-2 does not indicate absorbed radiation; of the infinite number of rays incident on the exterior wall barrier, some will be absorbed and will not emerge from the inner wall surface. Also much of the radiation, whether direct, scatter, or skyshine, emerging from the inner wall surface will travel on lines that will not be intercepted by the detector.

5. A large amount of radiation emerging from the inner wall surface would ordinarily miss the detector but could scatter in the air within the structure, scatter off the ceiling, or back-scatter from the opposite wall. Conceivably, such secondary interactions within the structure could result in an additional contribution to the detector above and beyond that of a primary nature considered in items 1, 2, and 3 above. With one exception, these secondary effects are minor in nature and are not considered in standard method calculations. The exception is ceiling shine. If the exterior walls contain large amounts of apertures, direct radiation from ground sources will pass through these apertures and impinge on the ceiling above the detector. Photons back-scattered from the ceiling (ceiling shine) can, in some cases, represent a significant portion of the total detector response. The standard method permits one to calculate ceiling shine contributions for such cases.

4-3.6 Calculation of Ground Contribution, Cg

Calculations for the ground contribution, through the walls of a structure are more complex than those for the overhead contribution.

Before proceeding with the calculations for the ground contribution to the detector in the basic blockhouse (Figure 4-1), it is necessary to consider more extensively some basic concepts, and to develop a fundamental understanding of several charts that will be used in a determination of Cg. These will be treated with considerable detail. They require extensive study and full understanding, without which, the meaning of the calculations cannot be clear.

Figure **4-5** shows, in section, a single-story, cylindrical structure with its floor at grade and with the detector centrally located 3 feet above the contaminated ground plane. It is assumed, that around the structure the radiating field is infinite in extent in all directions. In this discussion, only the contribution, Cg, through the walls will be considered. The walls of this structure are of a special character. They have a mass thickness approaching 0 psf. The structure is referred to as "thin-walled." The fact that the walls have no mass is of particular significance. In the absence of mass, any radiation incident upon the outside surface of the wall will pass directly through without absorption or scatter. Any radiation reaching the detector arrives on a direct line from the source either as direct radiation or skyshine radiation.

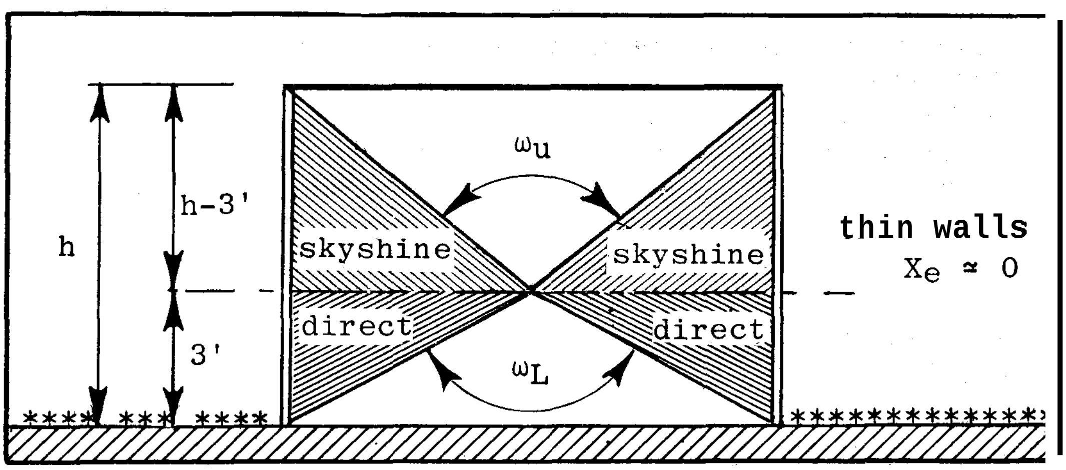


FIGURE **4-5**
THE THIN-WALLED STRUCTURE

Of interest in Figure 4-5 is the radiation which emerges from the inside of the exterior walls and reaches the detector from directions indicated by the shaded zones. These are complementary to the unshaded zones defined geometrically by the upper and lower solid angle fractions, ω_U and ω_L. In the solution for overhead contribution, solid angles were used to define the zone through which radiation passes; but in the case of ground contribution ω_U and ω_L are used to define zones through which wall emergent radiation does not pass in arriving at the detector. Regardless of this fact they may still be used as a parameter to interpret the effect of geometry on response to the detector through the shaded zones. Also, since there are more than one zone of interest, subscripts (U for upper and L for lower) are used to further define the solid angle fractions. As previously discussed, it is important to note that direct radiation, approaching the detector only through the shaded zone below the detector plane, includes an air-scattered component (skyshine) in addition to the major component that comes directly from the ground sources. It is termed direct purely for convenience. Through the shaded zone above the detector plane, only skyshine radiation approaches the detector.

As both the upper and lower solid angle fractions approach zero in Figure 4-5 the situation becomes identical with that of the standard unprotected location described in Chapter 3. As these solid angle fractions increase from zero, contributions through the wall decrease because the photons that would approach from the directions defined by the solid angle fractions, ω_U and ω_L, are eliminated from consideration. The reductions are, in both cases, purely functions of geometry since no barrier exists (other than air).

Spencer derived separate expressions for the response of a detector in the standard position to skyshine radiation from above and direct radiation from below. He expressed these as functions of solid angle fractions subtending discs free of contributing sources but surrounded by contributing sources extending infinitely in all directions. The cylindrical structure of Figure 4-5 would correspond to Spencer's solution for given values of upper and lower solid angle fractions.

The reduction in skyshine (air scattered) radiation response as ω_U gets larger and larger may be thought of as a "geometry reduction factor for skyshine radiation, or (for short) the "skyshine geometry factor," G_a.

G_a = Geometry Factor for skyshine radiation through that portion of a wall of a building lying above the detector plane, a function of upper solid angle fractions, $G_a(\omega)$.

The lower curve of Figure 4-6 gives the Skyshine Geometry factor as a function of solid cngle fraction ω, i.e., $G_a(\omega)$. Figure 4-6 is Chart 2 in Appendix C. Note that the scale for ω (the absissa) is an inverted logarithmic scale. This is due to the fact that although ω is used as a parameter to characterize the geometry effect, the actual skyshine contribution comes through the zone outside of ω, or the zone $(1-\omega)$.

To get the skyshine geometry factor $G_a(w)$, enter the curve with the value of the solid angle fraction wand proceed vertically to the skyshine curve. Go horizontally to read the Skyshine Geometry Factor $G_a(w)$ on the left hand scale. Example $\omega = 0.6$, $G_a(0.6) = .068$.

Unlike skyshine radiation which varies only negligibly with height, the angular distribution (section 3-6) of direct radiation is markedly affected by the height of the detector above the contaminated plane. Consequently, the Direct (Radiation) Geometry (Reduction) Factor G_d depends on both the solid angle fraction w, and the detector height H.

G_d = Geometry Factor for direct radiation through that portion of a wall of a building lying below the detector plane, a function of lower solid angle fraction and the height of the detector above the contaminated ground plane, $G_d(H, \omega)$.

Figure 4-7 gives Geometry Factors for Direct Radiation in terms of solid angle fraction wand detector height H. For the case of the basic block house being considered, the detector height H is 3 feet and $G_d(3', \omega)$ is read along the bottom of the chart, which represents H = 3 ft. When the detector height is more than 3 ft., such as in upper story location, the chart has a more general use. Take as an example the case in which $\omega = 0.6$ and H = 10 ft. Enter the chart with $\omega = 0.6$ along the bottom scale and proceed vertically until the horizontal line through H = 10 ft. (on the left hand scale) is intersected. Estimate the value of G_d at the intersection, i.e., $G_d(10, 0.6) = 0.64$. If the detector height H is 3 feet and ω remains at 0.6, the Geometry Factor for Direct Radiation is estimated to be: $G_d(3, 0.6) = 0.72$ (read along the bottom scale at $\omega = 0.6$ which is between $G_d = 0.70$ and $G_d = 0.75$. In Appendix C Figure 4-7 is divided into two charts at $w = 0.9$ and becomes Charts 3A and 3B. From Figures 4-6 and 4-7, it is noted that, for the extreme case in which, for a cylindrical, thin-walled structure, both the upper and lower solid angle fractions approach zero, the sum $G_d + G_a = 0.90 + 0.10 = 1.00$. This indicates that the normalized value of unity for the standard detector has been reached - that 100% of the radiation to which the standard detector responds has been accounted for.

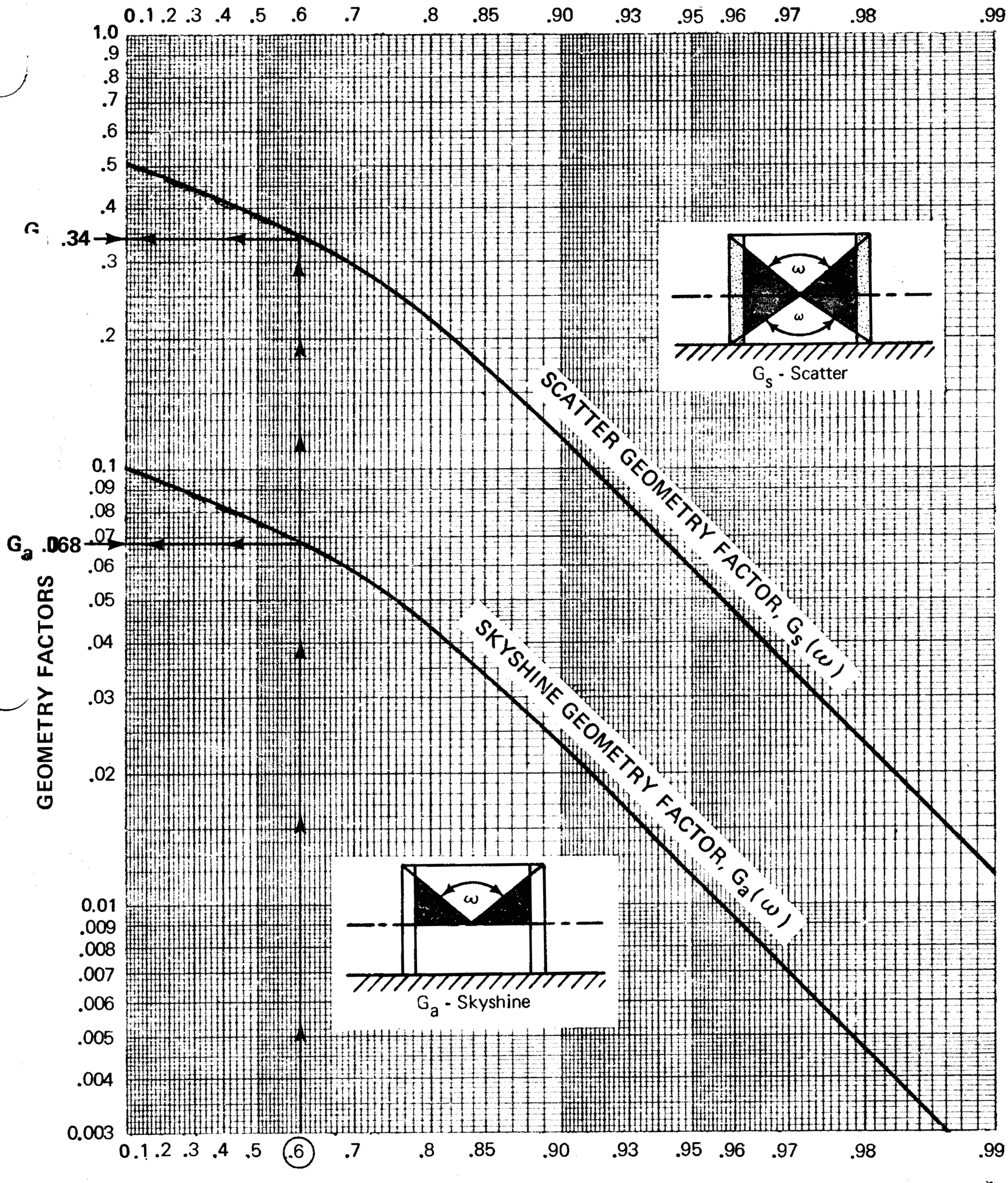
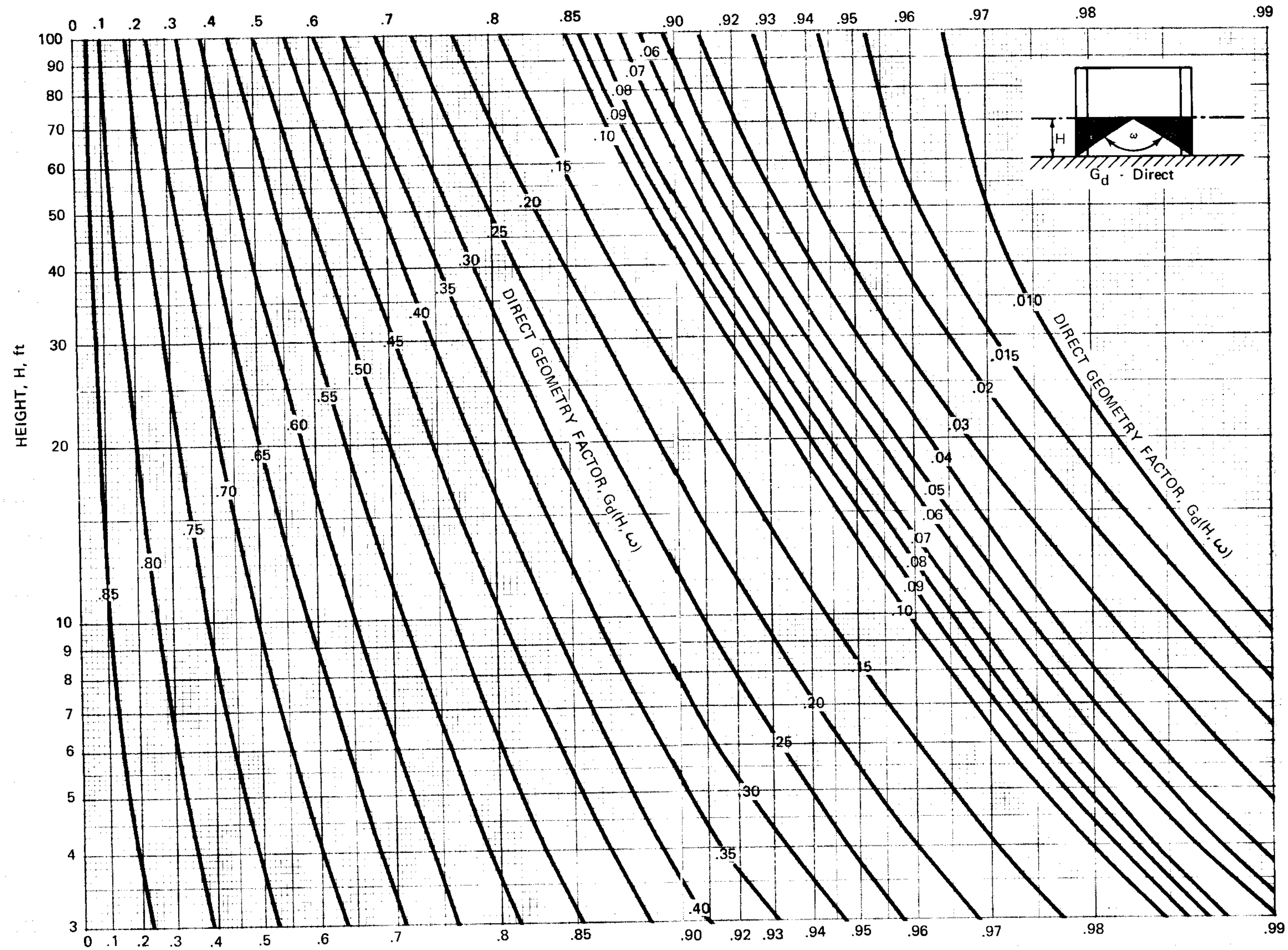


FIGURE 4 - 6 GEOMETRY FACTORS -SCATTER, $G_s(\omega)$ AND SKYSHINE, $G_a(\omega)$
(CHART 2 - APPENDIX C)



SOLID ANGLE FRACTION, ω

FIGURE 4 - 7

GEOMETRY FACTOR - DIRECT, $G_d(H,\omega)$

(CHART 3A and 3B Appendix C)

Although the geometry factors, G_d and G_a, of Figures 4-6 and 4-7 were derived from a consideration of cylindrical structures, they may also be used for rectangular structures. It is assumed that, if the solid angle fraction of interest in a rectangular structure is the same as that for a cylindrical structure, the geometry factors, G_a and/or G_d, will be equal. The basic concepts of the wall contribution through a thin-walled structure are illustrated in problem 4-2.

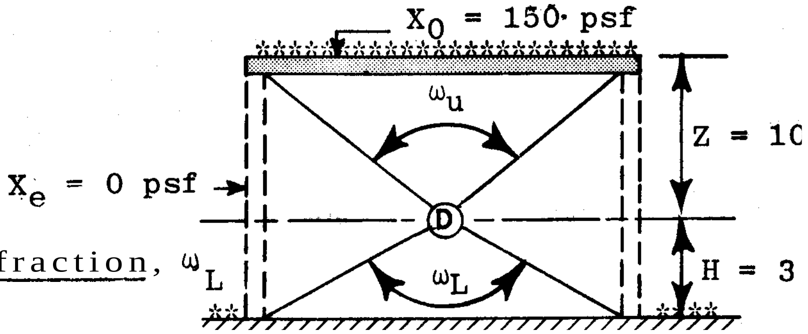
The solution to problem 4-2 gives a reduction factor of 0.52, indicating that geometry and barrier effects associated with the protecting building have reduced the contribution to 51% of that of the standard unprotected location The protection factor of 2.0 indicates that the standard detector receives 1/2 the radiation received at the protected location. Attention is also called to the relative magnitudes of the direct and skyshine contributions. The protection could be materially increased if the direct contribution could be eliminated, such as by depressing the building 3 feet into the ground. Complete burial, would eliminate all contributions except the overhead, and result in a PF of about 180.

Here we have considered a very simple situation, but it points out how the results of the calculations can be analyzed from the viewpoint of taking possible design measures to increase protection. This is of great importance in the process of "slanting" building design to enhance protection against fallout radiation.

The thin-walled structure represents one extreme in the concept of wall or ground contributions. The thick-walled structure is at the other extreme. Figure 4-8 represents, schematically, a section through a single-story, cylindrical structure having very thick walls. Again, only the exterior wall contribution will be considered in this discussion. The only interest at this time is in geometry effects. In the case of a thick-walled structure, it is impossible to completely separate geometry and barrier effects. If the walls of a structure are extremely thick, the chance that photons can pass directly through them to the detector without interaction is remote. It follows that the contribution to the detector consists entirely of wall scattered radiation from both the upper and lower wall segments. This is shown in Figure 4-8 where ω_u and ω_L are used to define the complementary zones through which scatter photons approach the detector. These complementary zones, shown shaded, indicate the scatter contribution that is left out of the total potential that would exist if both the upper and lower solid angle fractions were zero. As previously discussed in the thin-wall case, contributions approaching the detector through the directions defined directly by ω_u and ω_L are eliminated from consideration. Although only geometry reduction is of immediate interest in the discussion, it should be observed that very large exterior wall mass thicknesses would eliminate virtually all of the wall contribution through barrier reduction alone.

PROBLEM 4-2

The building of Problem 4-1 is selected and it is assumed that X_e=0 psf. The building is thus a thin-walled building. The detector responds to an overhead contribution (calculated in Problem 4-1), and to a wall contribution consisting of skyshine from the upper portions, and direct from the lower. The calculations below should be self-explanatory except to note, once again, no barrier effect for the wall.



W = 40'
L = 60'
H = 3'
X_o = 150 psf
X_e = 0 psf

Lower solid angle fraction, ω_L

$\frac{W}{L} = \frac{40}{60} = 0.67$

$\frac{Z}{L} = \frac{3}{60} = 0.05$ (Z = altitude of pyramid)

$\omega_L\left(\frac{W}{L}, \frac{Z}{L}\right) = \omega_L(0.67, 3.05) = 0.885$ (Chart A)

Upper solid angle fraction, $\omega_u = 0.64$ (Problem 4-1)

Wall (ground) contribution, C_g

$G_d(H,\omega L) = G_d(3, 0.885) = .45$

$G_a(\omega_u) = G_a(0.64) = 0.064$

$C_g = 0.45 + 0.064 = 0.514$

Overhead contribution, $C_o = .0043$ (Problem 4-1)

Reduction factor, RF

$RF = C_g + C_o = 0.514 + 0.004 = 0.52$ (rounded off)

Protection factor, PF

$PF = 1/RF = 1/0.52 = 2.0$ (approximately)

In the standard method, the geometry (reduction) factor for (wall)scattered radiation, G_s is defined as;

G_s = geometry factor for scatter radiation through the walls of a building lying either above or below the detector plane, a *function of either the upper or* ***lower solid angle fraction,*** $G_s(\omega)$.

Values for $G_s(\omega)$ are plotted in Figure 4-6. This curve was derived by assuming that angular distributions for thick-wall scattered radiation is similar to that for skyshine (which is also a scatter phenomenon). Thus, the shape of the angular distribution curve of thick-wall scattered radiation would correspond to that for skyshine as shown in Figure 3-4 ($\ominus$ between 90° and 180°). It was further assumed that angular distributions for $\ominus$ between 0° and 90° (below detector plane) would

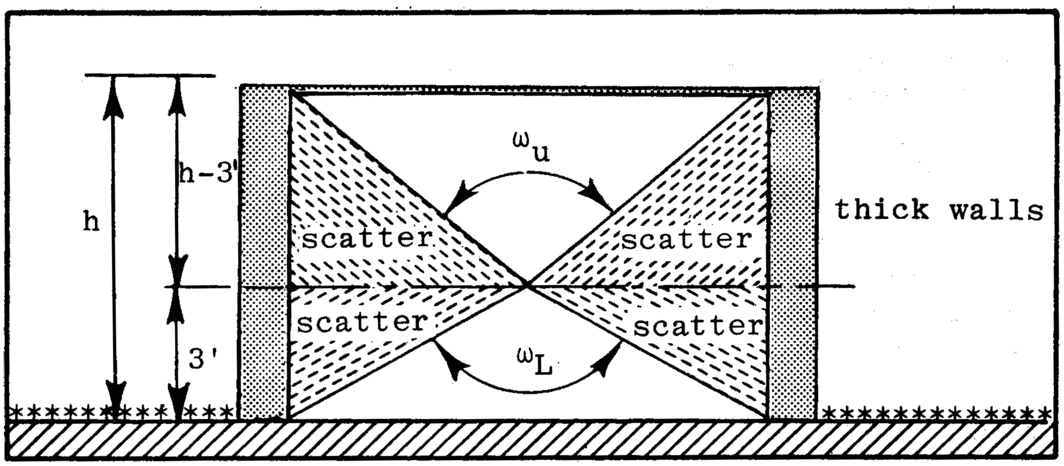


FIGURE **4-8**
THE THICK-WALLED STRUCTURE

plot as the mirror image of those for θ ranging between 90^{o} and 180^{o}. Now, if the total integrated dose angular distribution for the thick-wall case is to be the standard reference dose of unity, 0.50 must arrive at the detector from all directions above its plane and 0.50 from all directions below its plane. This immediately fixes the scale of G_s values as precisely five times those for G_a since the integrated skyshine dose from above the detector plane is 0.1, i.e. $G_a(\omega = 0)$ in Figure 4-6.

Referring to the G_a and G_s curves in Figure 4-6, it is observed, that, for a any value of ω, $G_s = 5G_a$. In a previous example it was determined that $G_a(\omega = 0.6)$ from Figure 4-6 (Chart 2, Appendix C) is found to be 0.34 which is exactly five times 0.068. It is further observed that, for $\omega = 0.0$, $G_s = 0.50$. Since both upper and lower solid angle fractions are involved, when both are zero, the unit reference dose is preserved. The inset figure adjacent to the curve denotes the necessity for considering G_s as a function of both upper and lower solid angle fractions, and shading of the walls is used to differentiate thick-wall from thin-wall geometry factors,

In the case of the thin-wall building it was assumed that geometry factors G_d and G_a derived on the basis of circular geometry are applicable to cases of rectangular geometry for equal values of solid angle fractions. Such is not the case for thick-wall geometry factors, G_s. As discussed above, G_s values plotted in Figure 4-6 (Chart 2 Appendix C) have been derived through representation of the thick-wall scatter response to the thin-wall skyshine response. Such representation implies that, for a given value of θ (Figure 3-4), scatter will be of the same intensity at every degree of azimuth just as in the case of skyshine. However, when a scatter interaction takes place in a wall, the most likely path for the departing photon to follow in emerging from the wall is the shortest path from the point of interaction to the point of emergence. This will be the normal direction, and thus there is the tendency for radiation to emerge from a thick wall in the direction normal to the wall. If the wall is circular, the normal directions of emergence are azimuthally symmetrical and representation of scatter response by skyshine has azimuthal correlation. Such will not be the case when scattering walls are not circular and emergence tends to be in directions perpendicular to the wall.

To correct for this effect in scatter geometry factors, G_s, an adjustment, the shape factor is applied as a multiplier to the scatter geometry factor, G, This factor is given by

$$E(e) = \frac{1 + e}{\sqrt{1 + e^2}}$$

where $e = W/L$ is the eccentricity ratio of the building.

E = a shape factor always applied as a multiplier to G_s (and only G_s) to correct for the shape of the building; $E(e)$.

The shape factor is normalized to unity for the case of a very long narrow building, since barrier factor data, which will be discussed later corresponds to such a case. For a square building ($e = 1.00$), $E = \sqrt{2}$ and for a cylindrical case it is $\pi/2$. Values of E(e) are plotted in Figure 4-9 which appears as Chart 4 in Appendix C. For a building 60 ft. by 40 ft. in plan, $E = \frac{W}{L} = 0.67$ and $E(0.67) = 1.39$.

The basic concepts of the wall contribution through a thick-walled structure are illustrated in problem 4-3.

The discussion, so far, has been limited to geometry factors for thin-walled and with thick-walled structures. Practically all real buildings have exterior walls that are intermediate in mass thickness between thin walls and thick walls. Figures 4-6, 4-7 and 4-9 (Charts 2, 3 and 4 in appendix C) are applicable to the direct determination of geometry factors for only thin and thick-wall structures. Spencer's work does not give similar data for walls of intermediate mass thicknesses. In view of this the method of analysis is based on taking a weighted average of thin-wall and thick-wall geometry factors for real cases. The weighing factor is termed the scatter fraction and is designated by S_w. It estimates the fraction of radiation reaching the detector that has been scattered at least once in the walls.

S_w = scatter fraction, that portion of the total radiation reaching the detector that has been scattered in the walls, a function of exterior wall mass thickness, $S_w(X_e)$.

Figure 4-10, Chart 5 in Appendix C, gives S_w as a function of exterior wall mass thickness. The figure S_w is entered with the value of the wall mass thickness X_e to obtain the scatter fraction $S_w(X_e)$. For example, if X_e is 100 psf, $S_w(100) = 0.775$ from Figure 4-10. The weighting factor S_w is applied as follows:

> Thick-walled geometry factors, G_s terms with shape factor correction (E), are multiplied by $S_w(X_e)$. Thin-walled geometry factors, G_a and G_d terms are multiplied by $1 - S_w(X_e)$.

The results are added to get the total geometry factor for ground contribution to the detector through the walls of a building of finite mass thickness. The rationale for the construction of the complete functional equation for the geometry (reduction) factor for ground contribution G_g is discussed next.

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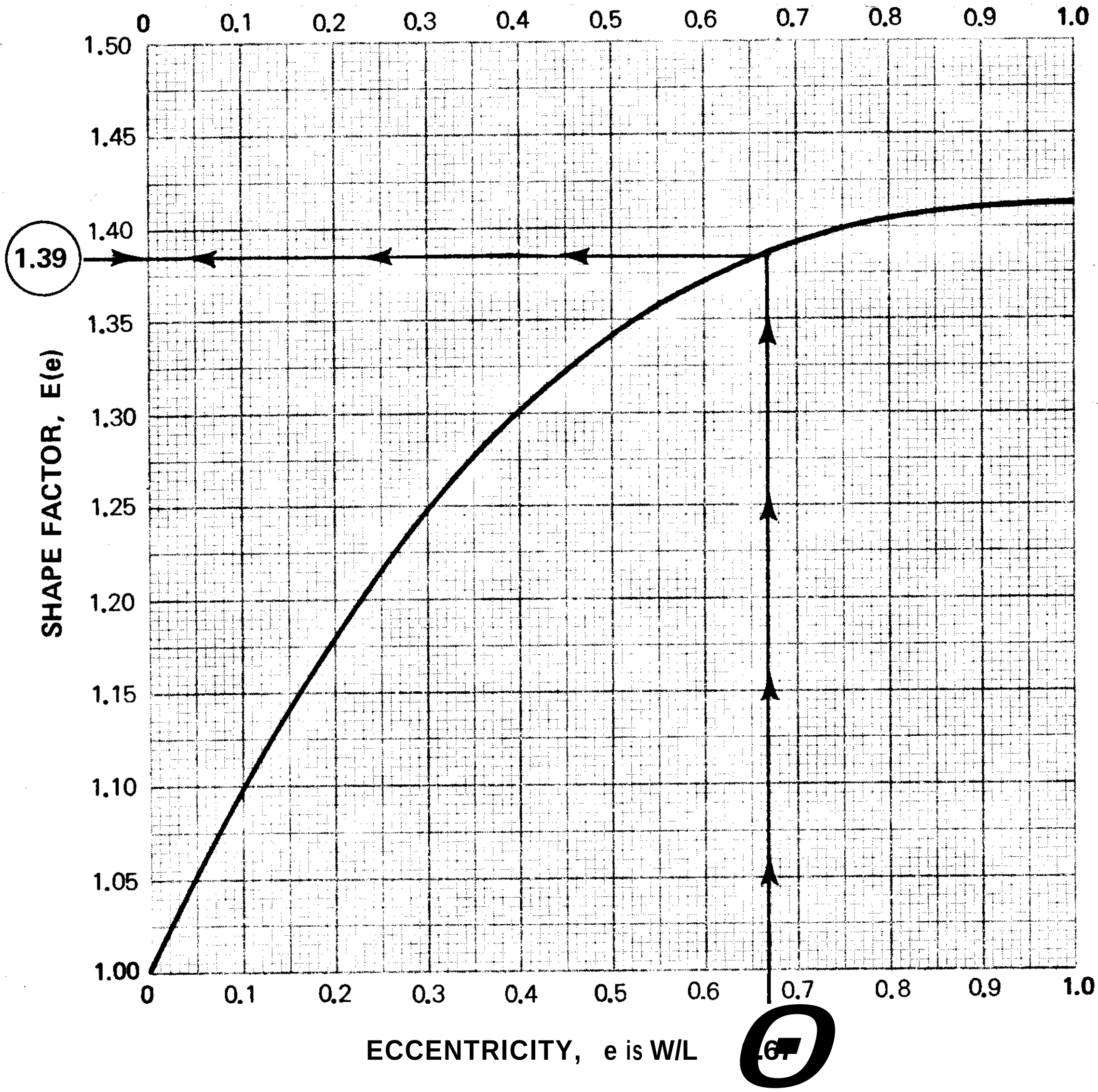
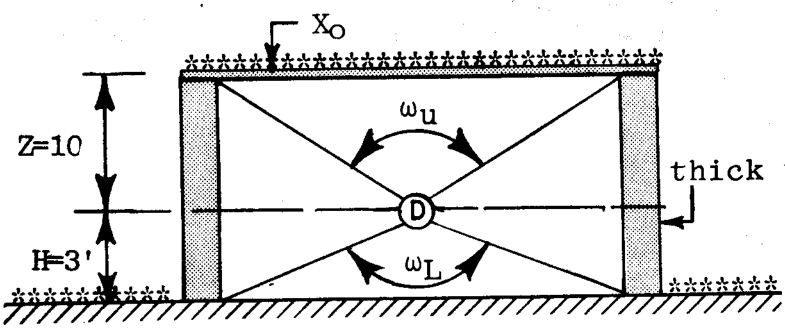


E (e) FOR CIRCULAR STRUCTURES IS $\frac{\pi}{2}$ = 1.571

FIGURE 4 - 9
SHAPE FACTOR, E (e)
(CHART 4, APPENDIX C)

PROBLEM 4-3

The building of Problem **4-1** (and 4-2) **is** again considered but in this case the wall mass thickness X **is** assumed to be very large, i.e., a thick-walled building.e **Only** the geometry effect of reduction in wall-scattered radiation are considered in this example.



?V = **40'**

L = **60'**

H = **3'**

X_o =(C_o will not be considered)

X_e = Very Large

Values of ω

ω_L = *0.885* **(Problem** *4-2)*

ω_U = **0.64** (Problem **4-2)**

Values G_s

$G_s(\omega_L) = G_s$ **(0.885)** = **0.135** (Chart **2)**

$G_s(\omega_u) = G_s$ **(0.64)** = **0.325** (chart 2)

~~Valu~~e of the shape factor, E

e = **W/L** = **40/60** = **0.67**

E(e) = **E(0.67)** = **1.39** (Chart **4)**

Scatter geometry reduction

$\{G_s(\omega_L) + G_s(\omega_u)\}\,E(e) = \{0.135 + 0.325\}\ 1.39 = 0.639$

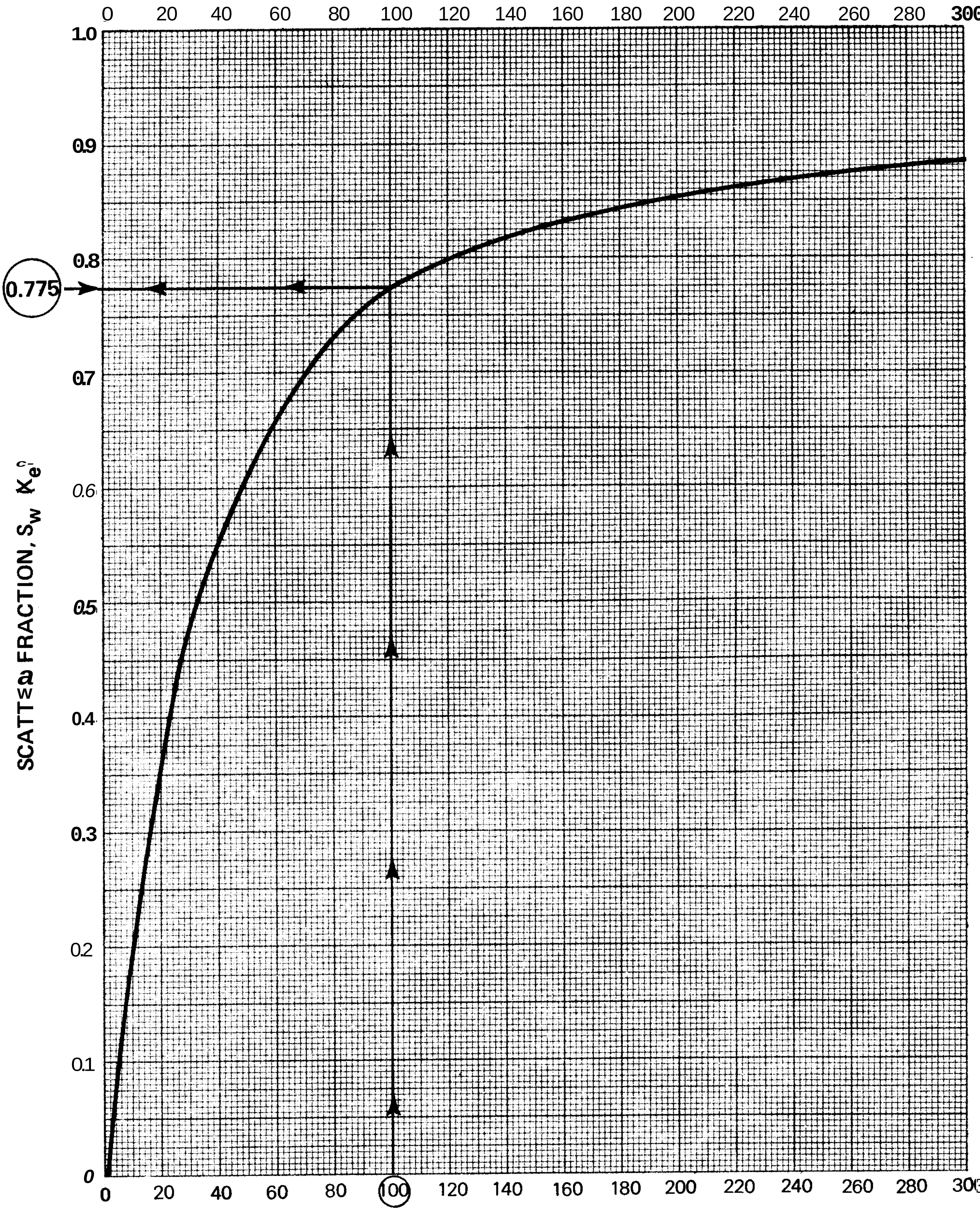


FIGURE 4 - 10
SCATTER FRACTION, S_w (X_e)
CHART 5 APPENDIX C

The geometry factor for the thin-walled structure is $[G_d(H,\omega_L)+G_a(\omega_u)]$. For the thick-walled structure, the geometry factor is $[G_s(\omega_u)+G_s(\omega_L)]E(e)$. For the structure of intermediate wall mass thickness, the geometry factor is the weighted average of those for the thin and thick-walled structures where the weighting factor is a function of the mass thickness of the exterior wall, X_e. Thick-wall geometry is multiplied by $S_w(X_e)$, thin-walled geometry by $[1-S_w(Xe)]$ and the results are added. The resulting complete functional equation for the geometry factor for ground contribution G_g for the simple blockhouse (Figure 4-1) is:

$$G_g = \left\{[G_d(H,\omega_L) + G_a(\omega_u)][1-S_w(X_e)] + [G_s(\omega_L) + G_s(\omega_u)]S_w(X_e)\cdot E(e)\right\}$$

G_g = total geometry factor for ground contribution.

It should be noted that, if the mass thicknesses of the upper and lower portions of the wall were different, upper and lower wall geometry would have to be separated because of the two different values of S_w involved. The analyst should study very carefully the functional expression for the geometry factor of intermediate wall mass thickness buildings. Strict attention should be given to the concepts involved rather than to a memorization of the symbols or the order in which they appear. This functional expression will be used consistently in practically all calculations involving the determination of protection factors in aboveground locations, and will be modified as other shielding parameters are taken into account. In learning fallout shelter analysis, emphasis should be placed on developing the ability to formularize the appropriate functional expressions through consideration only of basic concepts. (Symbols are of secondary importance.) If the basic concepts are well understood, no difficulty should be experienced in writing the proper functional expression for even the most complex cases.

So far, only geometry effects have been evaluated; in order to complete the determination of the blockhouse ground contribution C_g, barrier effects must also be considered. The geometry factor for ground contribution indicates to what extent geometry has reduced the contribution relative to the standard detector location. This is now modified by a barrier reduction factor which accounts for the effect of the exterior wall mass thickness in reducing radiation incident on the wall.

A barrier factor, B, can be defined as the fraction of radiation, incident at a point on one side of a barrier, that penetrates through to the other side. For example, a barrier factor of 0.10 would indicate that, of the radiation incident at a particular point on the barrier, only 10% will penetrate to the opposite face. In the case of the blockhouse, under consideration, the

detector is 3 feet above the contaminated plane (the standard height) and the barrier factor depends only on the mass thickness X_e of the exterior wall. When upper story detector locations are discussed, it will be seen that the exterior wall barrier factor will in addition depend on the height of the detector above the contaminated plane, due to (a) the mass of the intervening air, (b) the change in the dose rate angular distribution of direct radiation with height, and (c) reduction of intensity with distance from the source. These effects will be elaborated upon when upper story locations are considered, but to generalize the discussion of exterior wall barrier factors, the dependence on height will be included in the functional expression at this time. Therefore, the barrier factor for the exterior wall must be a function not only of the mass thickness of the wall but also of the height of the point of interest on the wall above the contaminated plane.

B_e = exterior wall barrier factor, a function of mass thickness and height, $B_e(X_e, H)$.

Since a particular wall segment would show different barrier factors because of different heights of points on the wall above the contaminated plane, it is necessary to select some point on the wall as an average point and consider the barrier factor associated with that point as constant for the entire wall. As indicated in the definition for B_e given above, the point selected should lie opposite the detector and hence the height of the wall point corresponds to the height, H, of the detector above the contaminated plane.

Using data generated by Spencer, Eisenhauer calculated exterior wall barrier factors as the ratio of; exposure at a point sandwiched between two vertical slabs of infinite height and length on an infinite-plane standard source to exposure at the standard unprotected location. The results giving barrier factors for exterior walls as a function of height and mass thickness are shown in Figure 4-11 (Chart 6 in Appendix C). It should be noted that the minimum value of H considered is 3 feet. If H is less than 3 feet, the value at 3 feet should be used. It is further noted that, for a mass thickness of exterior wall of 0 psf, the barrier factor for H = 3 feet is 1.00. A detector height of 7 ft. and an exterior wall mass thickness of 90 psf gives a barrier factor $B_e(7,90) = 0.1$.

It is now possible to complete the functional equation for the ground contribution for a simple one-story blockhouse. The ground contribution is the product of the geometry factor for ground contribution $[G_g]$ and the exterior wall barrier factor $B_e(H, X_e)$.

$$C_g = [G_g] \cdot B_e(H, X_e)$$

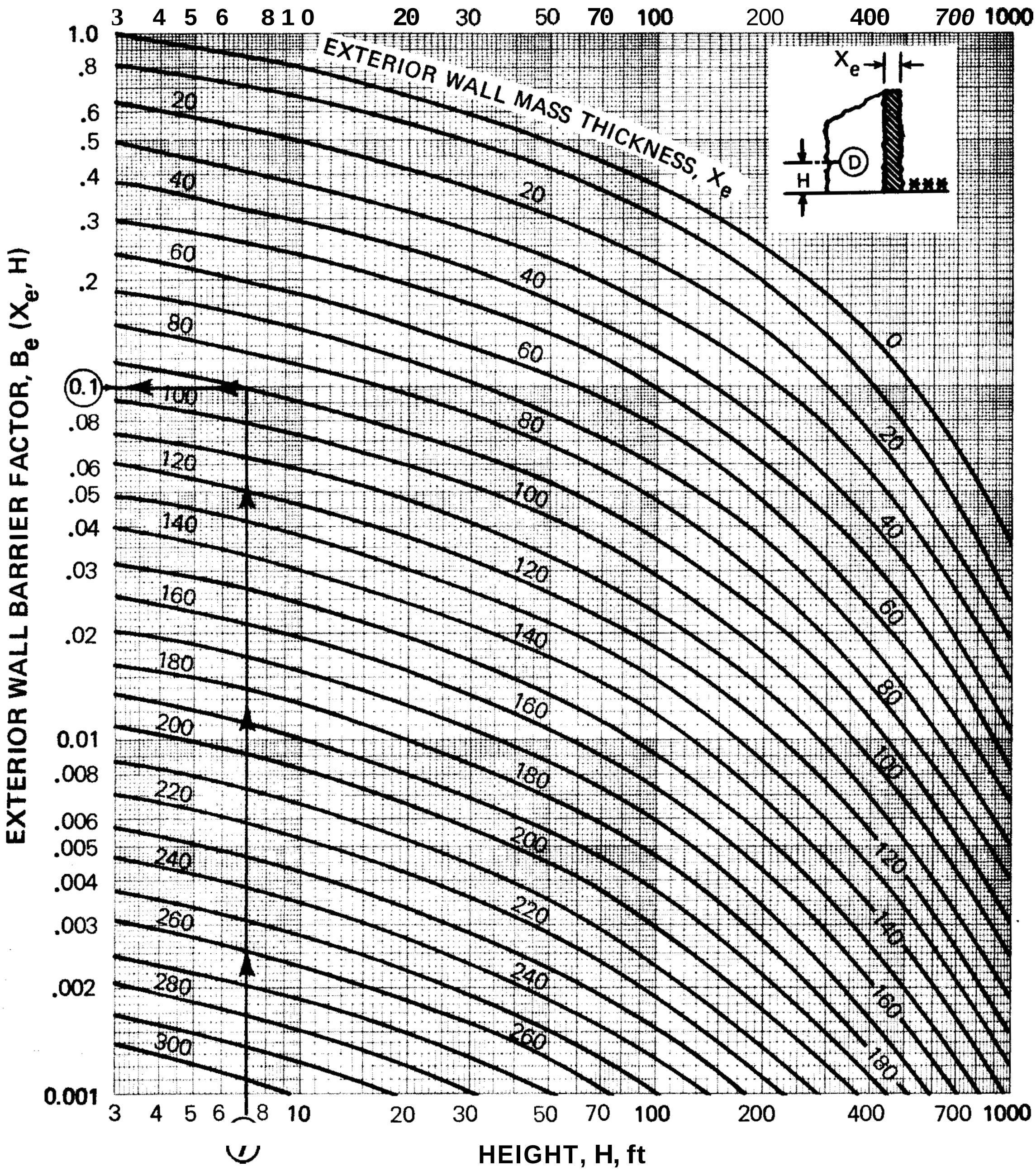


FIGURE 4 - 11
EXTERIOR WALL BARRIER FACTORS (Be(Xe,H)
(CHART 6 APPENDIX C)

4-3.7 Calculation of Blockhouse Protection Factor

The total blockhouse contribution consists of the Overhead Contribution C_o and the Ground Contribution C_g. Detailed calculation of Overhead Contribution was given in Problem 4-1. Components of the ground contribution geometry factor were calculated in Problems 4-2 and 4-3. These calculations are brought together in Problem 4-4, which shows the steps involved in determining the protection factor of a typical blockhouse.

The analyst should follow each step carefully being sure that he comprehends the meaning of all values and how they were obtained. Any difficulties can be cleared up by reference to the preceding material where the concepts have been discussed in detail. The solution begins with the basic data required, which consist of the dimensions of the building and the mass thicknesses of walls and roof. This is followed by a compilation of data taken from the appropriate charts. Of particular advantage is the manner, suggested in the solution, in which solid angle fractious and geometry factors are presented in tabular form. Such an arrangement lends order to the computations and allows them to be readily followed. Following the data compilation, the functional expressions for C_o and C_g are set up and solved. The reduction factor and protection factors round out the solution.

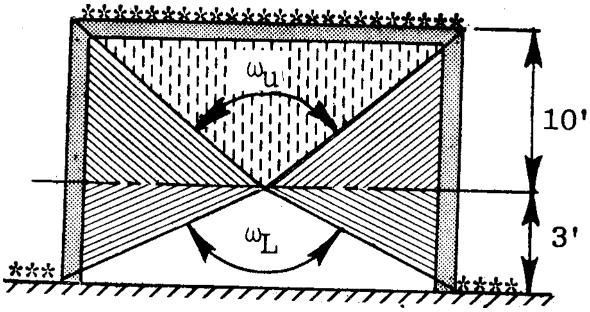
In the solution to Problem 4-4, note that the ground contribution C_g is larger than the overhead contribution by more than a factor of ten; and therefore (in this case) C_o has only a small effect on the protection factor. To increase the protection, the exterior wall mass thickness X_e would have to be increased. This would be a trial-and-error procedure since both $S_w(X_e)$ and $B_e(H,X_e)$ depend on the value of X_e. In other words, since X_e appears in both the geometry factor and the barrier factor, the ground contribution functional equation cannot be easily "inverted" for design purposes.

4-4 Blockhouse With Variation in Exterior Wall Mass Thickness

One conclusion that can be reached, in a qualitative interpretation of shielding parameters, is that an increase in the mass thickness of any barrier interposed between sources of radiation and a detector should result in a lesser contribution to the detector. In general, this conclusion is correct, but there are exceptions.

Consider the structure shown in Figure 4-12, and for the purpose of this discussion, let it be assumed that only the upper wall segment (that portion above the detector plane) contributes to the detector. In Figure 4-12(a) it is assumed that the upper wall segment has zero mass thickness. Normally, the

PROBLEM 4-4



$W = 40$ ft.
$L = 60$ ft.
$X_e = 100$ psf
$X_o = 150$ psf

	W	L	Z	W/L	Z/L	ω	G_d	G_s	G_a
ω_u	40	60	10	0.67	0.167	0.64	----	0.325	0.064
ω_L	40	60	3	0.67	0.05	0.88	0.45	0.135	-----

$E(0.67) = 1.39 \quad S_w(100) = 0.77, \quad B_e(3,100) = 0.093$

$$G_g = \{G_s(\omega_u) + G_s(\omega_L)\}\, E(e)\, S_w(X_e) + \{G_d(H,\omega_L) + G_a(\omega_u)\}\,\{1 - S_w(X_e)\}$$

$$G_g = \{0.325 + 0.135\}\{1.39\}\{0.77\} + \{0.77 + 0.064\}\{0.23\} = 0.492 + 0.118 = 0.610$$

$$C_g = G_g B_e(H, X_e) = 0.610 \times 0.093 = 0.0567$$

$$C_o(\omega_u, X_o) = 0.0043$$

$$RF = C_o + C_g = 0.0043 + 0.0567 = 0.061$$

$$PF = 1/RF = 1/0.061 = \underline{16}$$

upper wall segment would contribute both skyshine and scatter radiation to the detector. In the absence of mass thickness, no scatter can take place and the detector in Figure 4-12(a) receives only skyshine radiation from directions defined by the upper wall segment.

In Figure 4-12(b), the upper wall segment is assumed to have mass thickness greater than zero. Increasing the mass thickness above zero creates a dual effect with opposing results. A certain amount of skyshine radiation, which would ordinarily reach the detector through the zero mass thickness wall, will now be absorbed, and less skyshine will reach the detector. On the other hand, since mass has been added, the upper wall segment will begin to scatter radiation towards the detector as an additive quantity. For a certain range of mass thicknesses above zero pounds per square foot, the amount of radiation scattered to the detector may exceed the amount of skyshine absorbed, and the net effect on the contribution may be an increase. This effect is shown numerically in Problem 4-5.

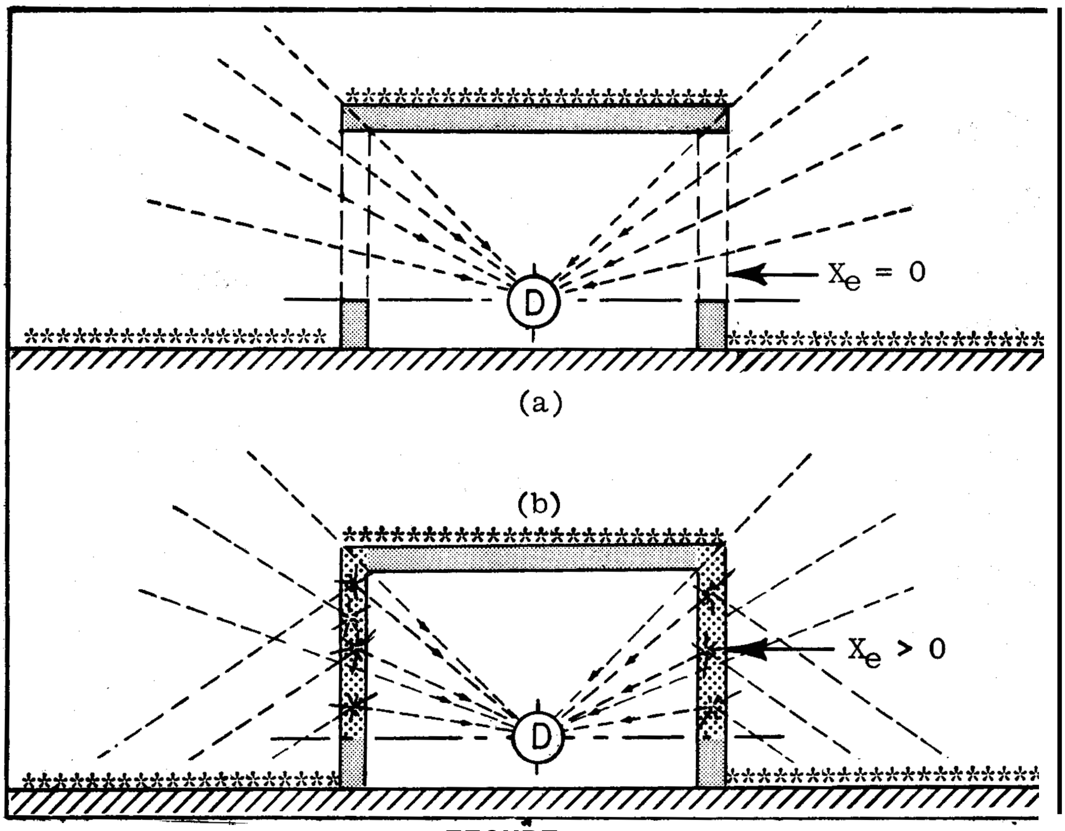


FIGURE 4-12
EFFECT OF INCREASING MASS THICKNESS ON SKYSHINE VS. SCATTER RADIATION

Problem 4-5(a) considers the normal wall contribution for a building having. 0 psf walls above the detector plane and 40 psf walls below. Since the mass thicknesses differ, it is necessary to calculate the contribution in two parts, that from above and that from below. It should be noted that the contribution from above consists only of skyshine radiation, since $S_w = 0$; and the scatter terms drop out. The functional equation has been written to include scatter in order to keep the equation general.

In part (b) of the problem, the ground contribution has been calculated for a mass thickness of 40 psf for all parts of the wall. The contribution from the lower wall portion is the same for parts (a) and (b), but it is noted that the contribution from the upper wall segment has increased from 0.068 to 0.107 when the wall mass thickness was increased from 0 to 40 psf. This is characteristic of low wall mass thicknesses. As the mass thickness is increased from 0 psf, the wall begins to scatter radiation into the detector. At first, the amount of radiation scattered in is greater than that absorbed by the barrier effect. This is true for mass thicknesses between 0 psf and about 35 to 40 psf. As the mass thickness is increased above 35 to 40 psf, the reduction due to the barrier effect begins to dominate, and the contribution begins to decrease. It continues to decrease with further increase in mass thickness. It should be noted that an attempt to increase protection by such measures as, for example, filling in apertures with material of low mass thickness may in some cases be to no avail and may, in fact, have the opposite effect (i.e. reduce protection).

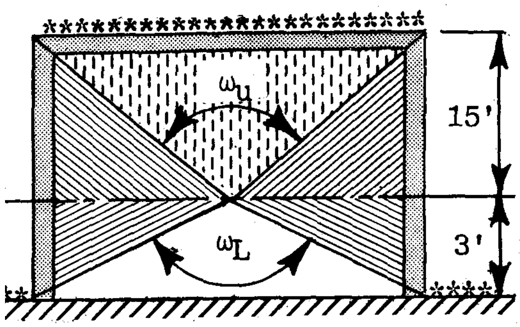
4-5 One-Story Blockhouse with Interior Partitions

4-5.1 Effect of Interior Partitions

The placement of interior partitions, between the exterior walls and the detector, results in a decrease in contribution from both the ground and overhead sources. Interior partitions furnish increased mass between the radiating sources and the detector. Hence, their influence on contribution is essentially an attenuation effect.

Figure 4-13 shows plan and section views of a single-story blockhouse with a centrally located detector completely surrounded by interior partitions. Figure 4-13(a) is a plan of the roof showing radiating particles uniformly distributed over its entire surface. The difference in shading is intended to indicate the position of the particles - some over the core area, defined by the boundaries of the interior partitions, and others over the peripheral area outside the partitions. Radiation coming from those particles over the core area and passing to the detector is not influenced by the partitions. That which originates over the peripheral area can reach the detector only after passing through a partition.

PROBLEM 4-5



W = **50 ft.**
L = 100 ft.
X_e = 40 psf (below Detector)
Part (a) X_e = 0 psf (above Detector)
Part (b) X_e = 40 psf (above Detector)
Note: Ceiling shine neglected

	W	L	Z	W/L	Z/L	ω	G_d	G_s	G_a
ω_u	50	100	15	0.50	0.15	0.61	-----	0.340	0.068
ω_L	50	100	3	0.50	0.03	0.915	0.038	0.100	-----

E(0.50) = 1.34, $S_w(40) = 0.55$, $S_w(0) = 0.0$

$B_e(3,40) = 0.38$, $B_e(3,0) = 1.00$

Part "a"
Portion of wall above detector:

$G_g = G_s(\omega U)\,E(e)\,S_w(X_e) + G_a(\omega_u)\{1-S_w(X_e)\}$

$= (0.340 \times 1.34 \times 0.0) + (.068 \times 1.00) = 0.068$

$C_g = G_g B_e(H,X_e) = 0.068 \times 1.00 = 0.068$ (above)

Portion of wall below detector:

$Gg = G_s(\omega_L)E(e)S_w(X_e) + G_d(H,\omega_L)\{1-S_w(X_e)\}$

$= (0.100 \times 1.34 \times 0.55) + (0.380 \times 0.45) = 0.245$

$C_g = G_g B_e(H,X_e) = 0.245 \times 0.38 = 0.093$ (below)

Total ground contribution = 0.093 + 0.068 = **0.161**

Part "b"
Portion of wall above detector:

$G_g = G_s(\omega_u)E(e)S_w(X_e) + G_a(\omega_u)\{1-S_w(X_e)\}$

$= (0.340 \times 1.34 \times 0.55) + (0.068 \times 0.45) = 0.281$

$C_g = G_g B_e(H,X_e) = 0.281 \times 0.38 = 0.107$

Total ground contribution = 0.107 + 0.093 = 0.200

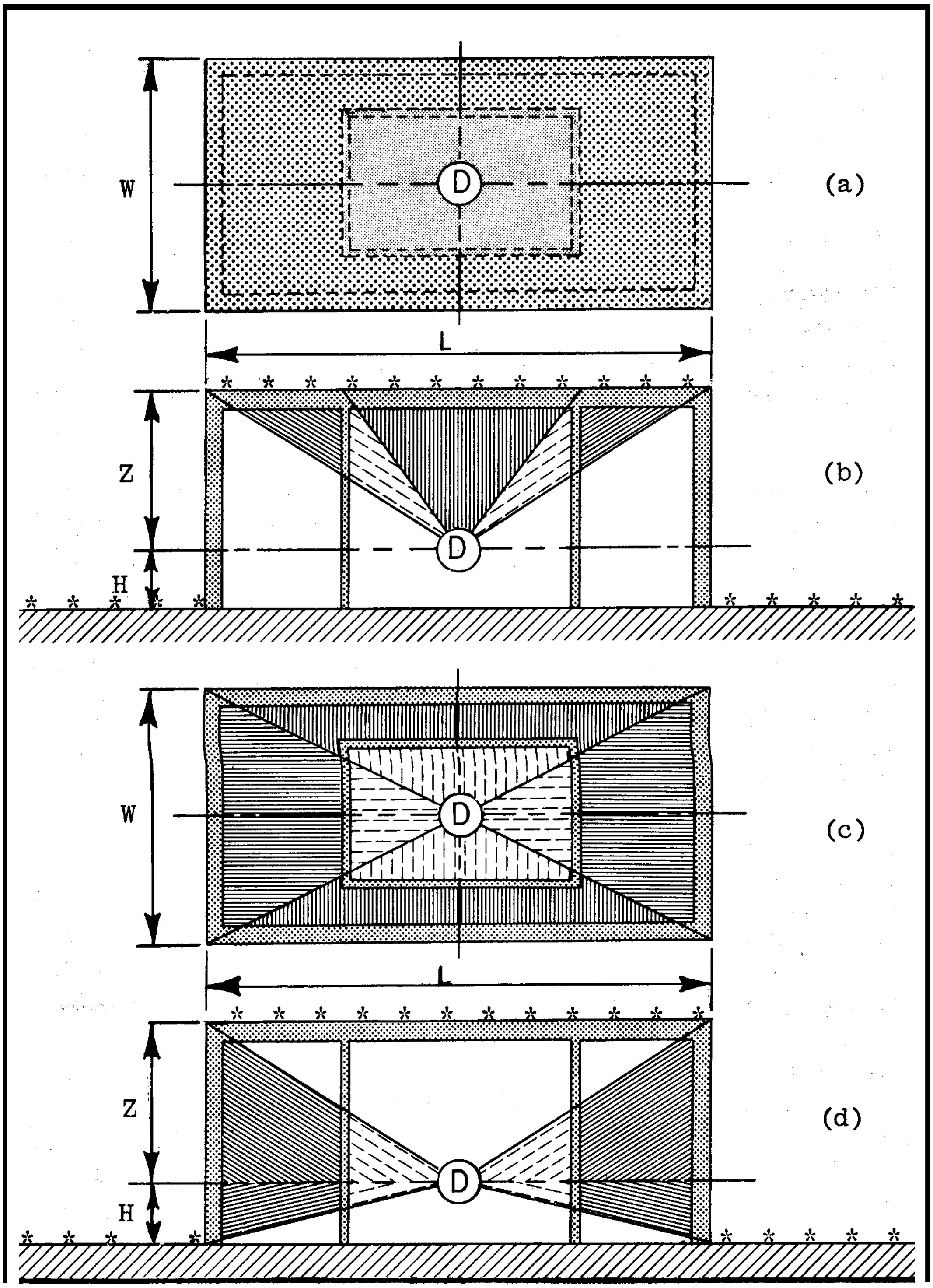


FIGURE 4-13
EFFECT OF INTERIOR PARTITIONS
ON DETECTOR RESPONSE

In so doing, it will be reduced' in infensity by virtue of the attenuation effect of the mass thickness of the partition. Thus, one of the effects of interior partitions is to reduce the amount of radiation reaching the detector from overhead sources. Figure 4-3(b) portrays this effect; the vertically hatched shading indicates a nominally uniform intensity of radiation approaching the detector from the underside of the overhead barrier. The broken line hatching indicates a reduction in intensity as a portion of the original rays are absorbed in the partition barrier.

Figures 4-13(c) and (d) show a similar effect with respect to ground (or wall) contribution. Radiation emerging from the inside, exterior wall surface and traveling on a path to the detector is attenuated as it passes through the interior partition. This is indicated pictorially in the figure by a change from solid line to dashed line hatching.

The overall effect of interior partitions is one of reducing both ground and overhead contributions and, consequently, increasing protection.

4-5.2 Attenuation Factors vs. Barrier Factors

Attenuation factors are applied as corrections to roof and wall contributions to account for the presence of interior barriers such as partitions, ceilings, and floors. An attenuation factor is defined generally as the ratio of a contribution at a point in a building with an interior barrier to the contribution for the same conditions but with no barrier. Attenuation factors are intended to account for both barrier and geometry effects, and are differentiated from barrier factors in which only barrier effects are accounted for. In the standard method of analysis, the term barrier factor applies only to the reduction of contributions through exterior wall barriers while the term attenuation factor applies to reduction through interior barriers.

The effect of placing interior partitions in the standard one-story blockhouse is to reduce both roof and wall contributions from what they would be if there were not interior partitions. Separate attenuation factors are required to evaluate wall and roof contributions because the angular distribution of radiation incident on the interior partition is different in each case. In the case of the wall contribution, emergence is from the roof perpendicular to the partition.

4-5.3 Partition Effect on Ground Contribution C_g

In the standard method it is assumed that the angular distribution of radiation incident on the interior partition is not significantly different fromthat on an exterior wall at a point 3 feet above the source plane. Further, interior

partition attenuation is assumed to be independent of the exact location of an interior partition relative to the exterior wall and the detector. Stated in another way, geometry is assumed to play an insignificant role for this type of attenuation factor. Therefore the inteior partition attenuation factor, B_i, applied to wall contributions is represented by the exterior wall barrier factor B_e at a height of 3 feet: $B_i(X_i)=B_e(X_e=X_i, H = 3.3)$.

$B_i(X_i)$ is given in Figure 4-14 also reproduced as Chart 7 in Appendix C. Following the discussion above, it is noted that the values for $B_i(X_i)$ coincide with those from Chart 6 for $B_e(H, X_e)$ when H = 3 feet.

It should be noted that H is not a factor in the evaluation of B_i. The effect of height is always taken into account only in the exterior wall barrier factor, $B_e(H, X_e)$, even though X_e may be zero. Since H is involved only in B_e, it is not permissible in the standard method to add partition mass thickness to exterior wall mass thickness to obtain a single barrier factor, $B_e(H, X_e + Xi)$. Figure 4-13(c) and (d) illustrates the effect of interior partitions in reducing wall contributions to the detector. In calculations, the functional expression for C_g becomes:

$$C_g = G_g B_e(H, X_e) B_i(X_i)$$

B_i = attenuation factor for interior partitions applied to wall contributions; $B_i(X_i)$.

X_i = average mass thickness of interior partitions in pounds per square foot of surface area.

Partitions contain openings which are ineffective in reducing the contribution. In the calculations, this is accounted for by taking X_i as the average "smeared" weight in pounds per square foot. For example, if the weight of the solid parts of a partition is 50 psf, and the partition contains 20% openings, X_i is taken as 80% of 50 or 40 psf.

If more than one partition intervenes between the exterior wall and the detector, the "smeared" mass thicknesses of these are added together to obtain a single value of X_i which then is used to determine a single partition attenuation factor applicable to C_g.

In problem 4-4 the ground contribution for a simple blockhouse without interior partitions was calculated as C_g = .0567. If interior partitions having a mass thickness X_i = 40 psf (and completely surrounding the detector) are added to the building, the interior partition attenuation factor for ground contribution

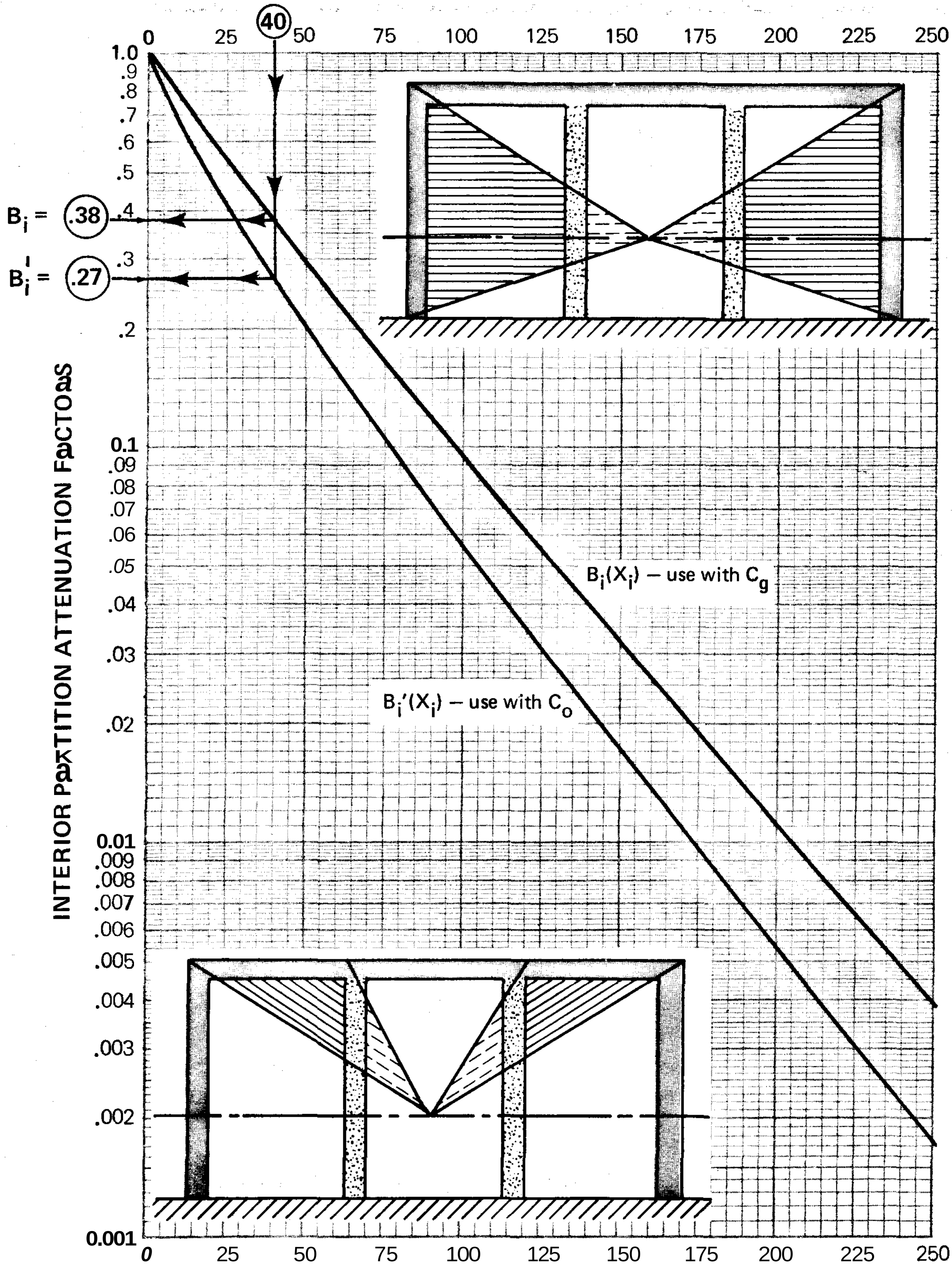


FIGURE 4 - 14

INTERIOR PARTITION ATTENUATION FACTORS, $B_i(X_i)$ AND $B_i'(X_i)$

(CHART 7 APPENDIX C)

$B_i(40)$ is 0.38. The ground contribution then becomes $C_g = 0.0567 \times 0.38 = .0215$.

It is emphasized again that, at this stage in the development of the standard method, only rectangular (or circular) buildings, with a centrally located detector and with symmetry about the detector axes in plan, can be analyzed. Complex structures lacking symmetry or with other irregularities will be considered later.

4-5.4 Effect of Partitions on Overhead Contribution, C_o

Figure 4-15 shows plan and section views of a single-story structure with a centrally located detector completely surrounded by partitions. Consideration is given to those sources lying on the core area and on the peripheral area of the roof shown in plan. The area included within the partitions is the core area and that outside the partitions is the peripheral area.

Referring to the section, it is observed that radiation, originating with fallout particles on the core area and passing to the detector through the zone defined by ω_o, is unaffected by the existence of the partitions. That originating with fallout on the peripheral area can arrive at the detector only by passing through the partitions where attenuation will occur.

Considering the entire roof and ignoring, for the time being, the partitions, the contribution for all roof sources, both core and peripheral, would be $C_o(\omega_o', X_o)$. Considering only the core area and ignoring, for the time being, the presence of partitions, the contribution would be $C_o(\omega_o, X_o)$. It follows that the contribution originating from peripheral sources is evidently the difference between the whole roof and core contributions, or, $C_o(\omega_o', X_o) - C_o(\omega_o, X_o)$. This peripheral contribution is affected by the partitions. A partition attenuation factor must be applied rendering $[C_o(\omega_o', X_o) - C_o(\omega_o, X_o)]B_i'(X_i)$ for the peripheral contribution to the detector. In this expression

B_i' = partition attenuation factor applied to overhead contributions; $B_i(X_i)$,

and all other symbols are as previously defined with X_i being taken as the average or "smeared" mass thickness of a partition with openings.

The total overhead contribution to the detector is evidently that from the core area plus that from the peripheral area, or,

$$C_o(\omega_o, X_o) + [C_o(\omega_o', X_o) - C_o(\omega_o, X_o)]B_i'(X_i).$$

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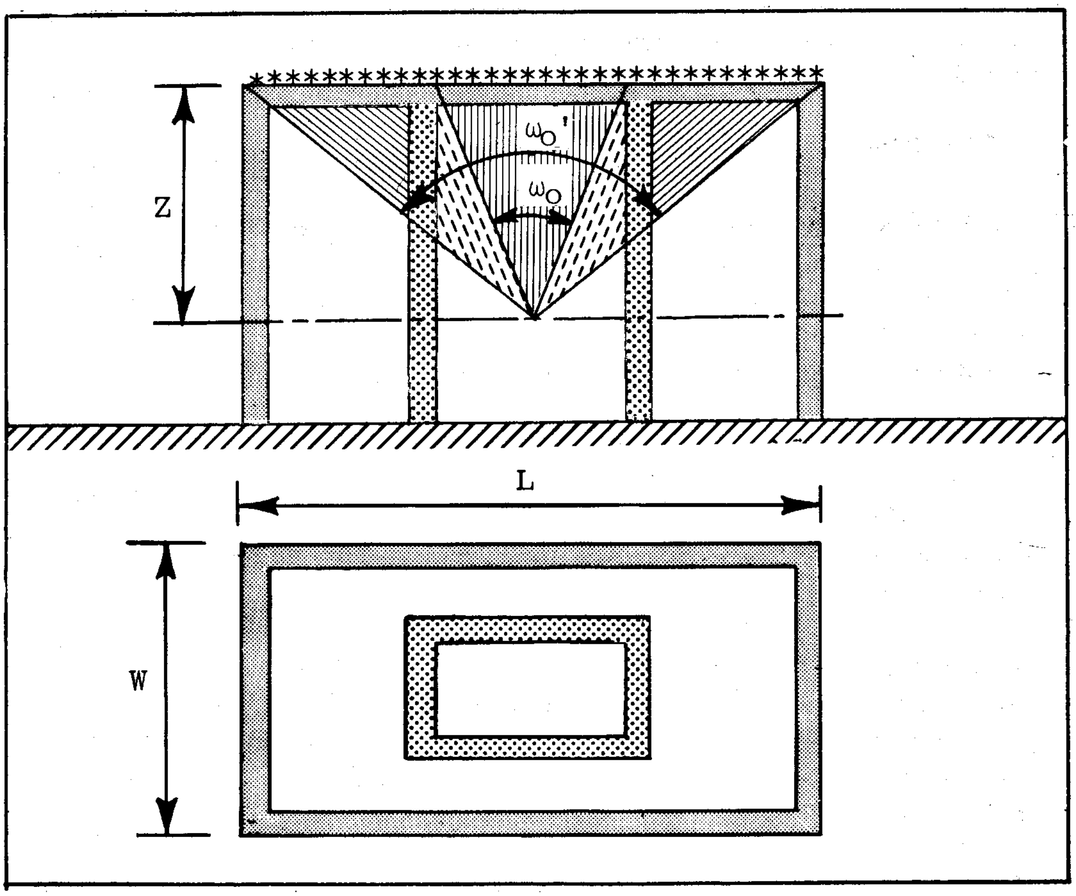

FIGURE 4-15

EFFECT OF **PARTITIONS ON** C_o